# Using Large Organic Debris to Restore Fish Habitat in Debris-torrented Streams

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## FISH/FORESTRY INTERACTION PROGRAM

This study was undertaken as part of the Fish/Forestry Interaction Program (FFIP), a multidisciplinary research study initiated in 1981. The program was started following a series of major winter storms in 1978 that triggered landslides over much of the Queen Charlotte Islands forest land base. Originating on steep slopes, many slides deposited tonnes of debris in streams and on valley flats. The events raised private and public concerns over logging practices on the Islands and prompted the establishment of the 5-year program. Overall objectives of FFIP were:

- to study the extent and severity of mass wasting and to assess its impacts on fish habitat and forest sites.
- to investigate the feasibility of rehabilitating stream and forest sites damaged by landslides.
- to assess alternative silvicultural treatments for maintaining the improving slope stability.
- to investigate the feasibility and success of using alternative logging methods, including skylines and helicopters, and by logging planning to reduce logging-related failures.

The program is jointly funded by direct appropriations from the Canada Department of Fisheries and Oceans, the B.C. Ministry of Forests and Lands (Research Branch), and the B.C. Ministry of Environment and Parks (Fisheries Branch). Participating agencies include the Canadian Forestry Service (Pacific Forestry Centre), and the Forest Engineering Research Institute of Canada (FERIC), Vancouver, B.C.

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For information about the program contact Ministry of Forests and Lands, Research Branch, 1450 Government Street, Victoria, B.C. V8W 3E7.

# Using Large Organic Debris to Restore Fish Habitat in Debris-torrented Streams

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## ABSTRACT

Large organic debris (LOD) was introduced into a small debris-torrented stream in 1982 in an attempt to increase the amount of pool habitat available for overwintering coho. After one winter, the number of pools present in an experimental section of the stream increased from four to fourteen, the number of pool types increased from three to six, pool area increased from 2.5 to 18.4%, and LOD cover increased from 2.2% of the wetted stream area to 11.2%. After a torrent-like summer flood and a second winter, the number of pools present had increased again to 21, while the amount of LOD cover and pool area was 17.7 and 15.4% of the total stream area available, respectively. By comparison, pool number, pool diversity, pool area, and LOD cover all remained relatively constant in a control section over the same time period. The stream was torrented again in spring 1985, at which time the only structures still in place and functioning, were those that had been cabled to trees and stumps alongside the stream.

Compared to a control section, coho overwinter survival in the experimental section increased from 13 to 52% in the 1st year, while smolt production increased from 290 fish per kilometre of stream to 1050 fish per kilometre. The second year, coho survival declined to 10% and smolt production to 140 fish per kilometre of stream, but both were still considerably higher than those in nearby torrented streams without new LOD. Benefit/cost analysis based on the first year's results indicated that the benefits derived from increases in coho production could pay for the cost of new LOD emplacements after five or six years, as long as there is no more mass wasting. Because three LOD emplacements were still creating new rearing habitat after a debris torrent, restoring LOD in streams is considered to be a realistic and feasible way of offsetting some of the impacts of mass wasting in productive fish habitats. Further studies are now needed to determine what LOD configurations can be used to manipulate stream flows more precisely and improve fish spawning and rearing habitats. Such structures must be able to accommodate recurrent large scale sediment movements without blocking the stream and without being destroyed.

## ACKNOWLEDGEMENTS

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# 1 INTRODUCTION

Large organic debris (LOD) usually plays an important role in determining the morphological diversity of small forested west coast streams (Swanson *et al.* 1977; Swanson and Lienkaemper 1978; Keller and Talley 1979; Bisson and Sedell 1984). It does so primarily by acting as hydraulic controls that, in steep streams, slow or buffer an otherwise rapid downstream movement of debris, sediments, and organic nutrients. By creating obstructions and impeding flows, the presence of LOD also increases the number of sites where localized scouring and deposition occur, and in turn, the number of stable sediment storage sites and pool habitats present. Stable sediment deposits between pools are a desirable feature of good spawning areas for adult fish (Hall and Baker 1975), while the pools themselves when associated with LOD usually represent critical rearing and overwintering areas for juvenile fish (Hartman 1965; Bustard and Narver 1975; Tschaplinski and Hartman 1983; Heifetz *et al.* 1986).

In the steep coastal regions of British Columbia, streams that lack stable LOD or other hydraulic controls such as boulders or bedrock tend to lack good spawning and rearing areas as well. This is particularly evident in streams "sluiced out" by landslides that start in the headwaters and move downstream as debris torrents, into productive fish habitat. During a debris torrent, most of the LOD and sediments once present in the steep upper reaches of a stream are carried downstream, leaving behind a series of cascading riffles with a bouldery substrate. Downstream in the typically more productive low gradient reaches, the damage is usually greater because this is where the LOD and sediments, originally present upstream, are eventually deposited. In these reaches, the original stream channel may be gouged out to two or three times its original width and then subsequently refilled with an excess of debris and sediments from upstream (Tripp and Poulin 1986a). The stream is channelized, virtually all pools disappear, and braiding or dewatering caused by excess sediments may be a serious problem at low flows. Most of the surrounding vegetation is lost, while whatever LOD still left is either buried or piled up into immense windrows and jams that do little to stabilize sediments or increase the morphological diversity of stream channels (Hogan 1985).

A number of steps are involved in the recovery of streams affected by debris torrents and landslides (Lisle 1981); however, probably the most important to fish is the re-establishment of stable pool/riffle sequences. In the steeper reaches of otherwise undisturbed basins, this last step may actually occur quickly if the loss of debris-controlled pools is compensated by the formation of new boulder or bedrock-controlled pools, until new LOD falls into the stream channel from the adjacent forest. By comparison, the recovery of lower gradient stream reaches in recently logged areas is almost certain to be much slower. First, there are invariably fewer boulders or bedrock outcroppings to serve as alternative scouring agents. Second, the absence of a mature forest alongside a stream effectively means that no new LOD will be added to the stream until at least one tree species in the riparian zone is well established and starts to die (Bryant 1983).

Because it increases the amount of localized scouring the re-introduction into streams of LOD and other "roughness agents" (Lisle 1982), such as boulders, has been recognized for some time as a potentially effective way of enhancing fish productivity, (Salmonid Enhancement Program 1981). Undoubtedly a number of projects have in fact already used LOD this way; however, to date very few give a detailed evaluation of their success. In British Columbia, the use of boulders was systematically evaluated in the Keogh and Salmon rivers on Vancouver Island and found to be a cost-effective way of increasing steelhead trout production, but only in relatively stable streams (Ward and Slaney 1982). Comparable studies are still needed on the use of LOD structures.

In this study, the feasibility of using LOD to improve 'damaged' stream habitats was assessed over a two-year period in a debris-torrented stream on the Queen Charlotte Islands, British Columbia. The main objectives of the study were:

1. to determine if LOD could be re-introduced into debris-torrented streams to increase localized
2. to determine whether or not the increases in pool habitat would also increase coho overwinter survival and thus coho smolt production;
3. to compare the benefits of increased coho smolt production with the costs of replacing LOD in debris-torrented streams.

## 2 STUDY AREA

The study was conducted in the first 500 m of Southbay Dump Creek, a small, 3.2 km long coho salmon stream on the north side of Moresby Island in the Queen Charlotte archipelago, British Columbia (Figure 1). Located within the Queen Charlotte subzone of the coastal western hemlock biogeoclimatic zone (Banner and Pojar 1982), the main climatic features of the area are "...cool summers, mild winters, a prevalence of cloudy skies and strong winds, and excessive late fall and early winter precipitation" (Calder and Taylor 1968). In Southbay Dump Creek mean annual precipitation is estimated to be at least 200-225 cm (Hogan 1985), less than 15% of which falls as snow. Over the period of record, September 1982 to July 1984, mean monthly summer flows in Southbay Dump Creek ranged from 0.04 to 0.09 $m^3/s$, with winter peaks averaging 1.36 $m^3/s$ (±2.71, 2SD, N=52, Range 0.10-8.89 $m^3/s$).

The study area included a Control Section over the first 185 m of stream and an Experimental Section over the next 315 m (Figure 1). During the summer low flow period, both sections initially averaged 2-3 m in width and followed a straight course over a wide, open floodplain. The floodplain itself was dominated by bare, flat-topped gravel deposits extending more or less from valley wall to valley wall, an average width of 21 m. Banks other than those formed by valley walls or gravel berms were essentially non-existent and largely ineffective in confining the stream during even moderate freshets. At these times the stream would frequently spread across the entire valley flat, sometimes shifting channels altogether. Before the study began, initial surveys indicated a stream composed primarily of cobble-bedded riffles with relatively little cover for fish (pools, boulders, undercut banks, vegetation or LOD), regardless of stage height, either instream or on the floodplain. Stream gradient ranged from 2.9% in the Control Section to 4.0% in the Experimental Section. The mean was 3.7%.

Approximately 81% of Southbay Dump Creek's watershed had been logged by 1985 -- 33% of it from 1961 to 1968 when most of the lower reaches, including the riparian zone, were cut; and 48% from 1977 to 1980 when the remainder of the lower reaches and most of the upper reaches were cut. In both periods, log removal involved high-lead cable systems combined with an extensive network of roads and landing sites. Many of the roads crossed steep and inherently unstable terrain, and several subsequently failed, either because of weaknesses in the roads themselves or failures on the hillslopes above them. Soils for the most part are generally shallow (<1 m) colluvials composed primarily of ferro-humic podzols above easily eroded sedimentary rocks. The total number of slides and flows in the watershed was 39, for an overall failure frequency of 9.7 per square kilometre (Rood 1984).

Mass wasting, including slides, slumps, and torrents, has long been the dominant geomorphic process in Southbay Dump Creek; logging, however, clearly accelerated the process. In October 1978, the first of four debris torrents (after logging) sluiced out the entire stream and left an impassable debris jam at the mouth. The first jam was removed, but a second torrent in February 1979 formed another impassable jam which, until the spring of 1985, was still in place 900 m upstream. A third torrent-like flood restructured the stream on August 2, 1983, re-burying the upper 200 m of the study area, while a fourth torrent disrupted the upper 300-400 m of the study area in spring 1985, after this study was completed.

There are no salmon escapement records for Southbay Dump Creek, although it was reputed to have had at one time "reasonably good runs" of both chum and coho salmon. Routine surveys conducted during 1982 indicated 19 coho and 4 chum salmon adults in the creek, with the coho extending at least 600 m upstream from the mouth. Chum salmon probably migrate only 400 m upstream, and in most years only 250 m. Dolly Varden char ascend at least as far as the debris jam 900 m upstream. Sculpins (both *Cottus aleuticus* and *Cottus asper*) inhabit at least the lower 300 m.

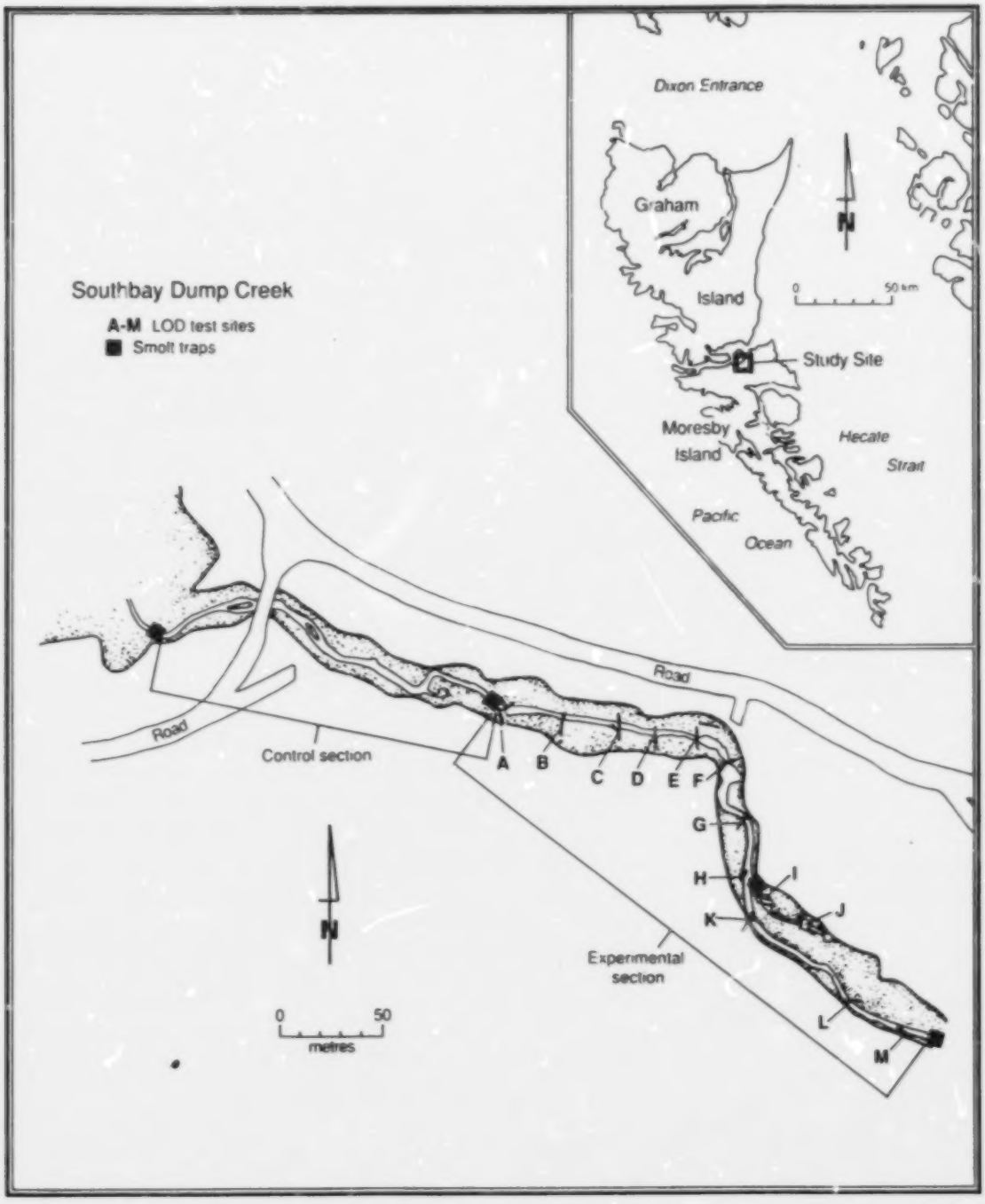


FIGURE 1. Southbay Dump Creek showing the Control and Experimental sections, LOD test sites, and downstream smolt traps.

# 3 METHODS

## 3.1 LOD Installations

On August 16-18, 1982 one to four pieces of large organic debris were placed with the aid of an FMC log skidder at each of 13 sites in the Experimental Section of Southbay Dump Creek (Figure 1). Eleven sites (Sites A to H, K, L) were spaced an average of 30 m apart along the mainstem portion of the creek, while two sites (I and J) were located 22 m apart on a sidechannel. Mean length of the LOD used was 7.9 ± 3.5 m (ISD, N=24, Range 2.0-15.0 m); mean diameter (measured midway along the bole with a meter stick) was 0.8 ± 0.5 m (Range 0.2 - 2.7 m).

The amount and type of LOD used at each site depended largely on what was available in the immediate vicinity of each site. Also important was the number of anchor points present (i.e., stable debris, rooted stumps, trees, non-erodible banks,) against which LOD could be wedged or to which it could be attached with 2 cm diameter logging cable. Only LOD that appeared heavy enough to remain stable during a major flood (e.g., at Sites B, C, H, K, L, M) was used where suitable anchor points were lacking. Where LOD was lacking altogether, logs from the estuary were used instead (e.g., at Sites E, F, and G).

At some sites more than one piece of LOD was used to protect a streambank (Sites A and E) or block off a greater portion of the valley flat (Sites B and D). At other (Sites C, G, and K), extra pieces were added to increase the number of scour points at each site and thus the complexity of the pools. Although no sites were replicated exactly, two types of structures were tested in the mainstem creek, including (see also Figure 2):

1. cross-stream obstructions at seven sites (B to H), made up of one main log or rootwad spanning the stream at approximately 90° to the direction of flow, partially or completely blocking off stream flows in the process;
2. oblique obstructions at four sites (A, K, L, and M), made up of one main log placed diagonally across the streambed at approximately 45° to the direction of flow, with rootwad ends either upstream or downstream.

Of the seven cross-stream structures, five sites (B, C, D, G, and H) were logs or rootwads that rested flat on the streambed to deflect flows downward and scour out a pool underneath the LOD. Two sites (E and F) were logs installed 0.3 m into the streambed and then filled in upstream to form log sills over which the stream would flow to scour out a plunge pool downstream. The four oblique arrangements (Sites A, K, L, and M) all rested flat on the streambed to promote lateral scouring underneath and alongside each piece. To form pools at Sites E and F (with log sills) and A, K, and L (with oblique arrangements), gravel was scraped from the streambed and banked against the upstream side of the LOD, temporarily damming up the stream.

The two side channel sites (I and J) were an attempt to provide off-channel overwintering areas for coho fry. Two pools were excavated in the side channel with the blade of the FMC: the first (Site I), 26 $m^2$ in area with a maximum depth of 0.41 m; and the second (Site J), 14 $m^2$ in area with a maximum depth of 0.41 m. LOD was added to the first pool to provide overhead cover (logs spanning the pool, just touching the water surface); while in the second pool, LOD was added to provide instream cover (LOD resting on the bottom of the pool, partly or wholly submerged). The side channel itself was a "debris-capped" side channel (Sedell *et al.* 1984) formed by water seeping out from the base of a debris jam.

## 3.2 Mapping and Habitat Evaluations

A combination of standard survey methods and low-level aerial photographs were used to record changes in channel thalweg, stream margins, pool/riffle/glide boundaries, and LOD placement. For the standard surveys a theodolite, survey chains, and stadia rods were used; for the photographic surveys a SLR camera and 25 mm lens mounted on top of a 9.1 m long steel pole were used. A gimbaled mounting bracket held the camera horizontal to the ground when it was suspended in the

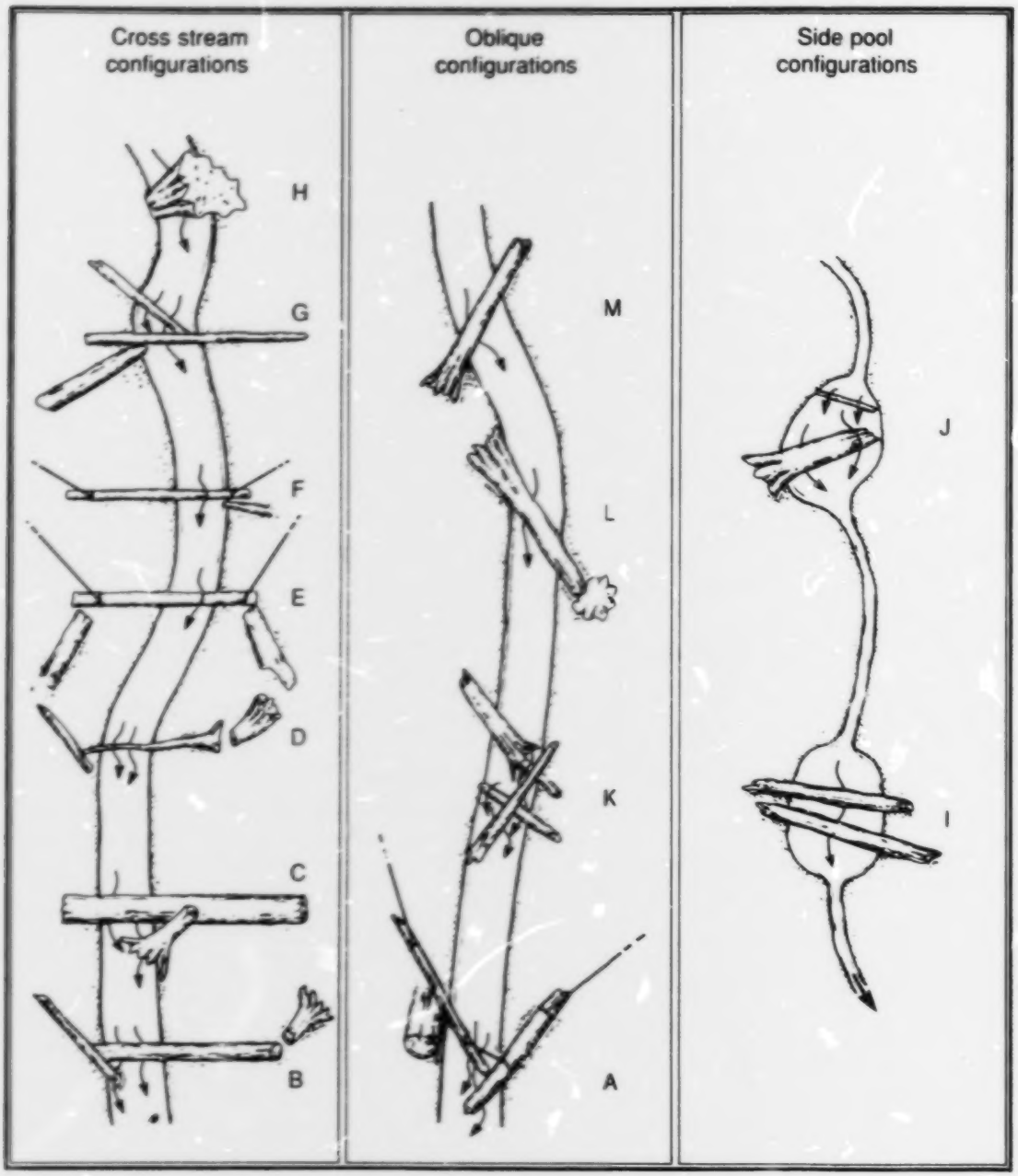


FIGURE 2. Diagrams of the LOD placed at each test site (A to M), in Southbay Dump Creek, August 16-18, 1982.

air, stadia rods were laid on the ground for scale. A 10m long pneumatic cable released the shutter. Altogether four maps were made, one each for the early and late summer-fall periods of 1982 and 1983.

Routine habitat inventories were conducted in conjunction with the mapping surveys, at which time the type of pools, glides, and riffles present was recorded according to Bisson *et al.* (1982), along with stream areas, depths, and the amount of stable LOD cover present ($m^2$). To be designated as LOD, debris had to be at least equivalent in volume to a stem or branch 3 m long and 0.1 m in diameter. LOD cover itself was defined as any LOD lying within the lateral confines of the wetted channel at the time of the survey, and within 1 m of the water surface. To be designated as cover, a portion of the debris also had to be immersed in the water and providing some minimal reduction in water velocity.

### 3.3 Fish Sampling

Juvenile coho densities were estimated separately in the Control (estuary to 220 m upstream) and Experimental (220-540 m upstream) sections of Southbay Dump Creek each time the stream was mapped, with additional estimates made in the Experimental Section immediately before and after the LOD was placed in the stream. For the latter estimates, a removal method was used where individual features (pools, glides, riffles) were enclosed with fine-mesh stop-nets and fished (Smith Root VIII A electroshockers and minnow seines) with two or three successive equal efforts, until numbers of fish in the last catch were zero or nearly so. Depending on the number of fishing efforts, population numbers by species and age class in each feature were then calculated according to Seber and LeCren (1967) or Zippin (1956, 1958). Fish densities for the whole Experimental Section were estimated by summing the products of the mean densities (± 2SD) calculated for pools, glides, and riffles and the proportions of pool, glide, and riffle habitat present.

A Peterson mark-recapture technique was used at all other times to estimate the number of juvenile coho present. At these times, fish were first collected over the entire length of each study section, marked with right or left partial pelvic fin clips, and redistributed according to the number of fish originally captured in each pool, glide, or riffle. In a second sample 6-24 hours later, marked and unmarked fish were recorded separately for each feature, and the total number of fish present was estimated according to Bailey (1951). To determine confidence limits at the 95% level, the number of recaptures R was treated as a Poisson variable and the upper and lower limits for R were obtained from a table in Ricker (1975, Appendix II).

To count the number of coho smolts moving out of Southbay Dump Creek, three separate downstream trap and weir facilities, similar to those of Tripp and McCart (1983), were placed during the spring at the lower and upper ends of the two study sections (Figure 1). A fourth trap was located at the mouth of the side channel tributary in the Experimental Section. Over their period of operation--April 18-June 10 in 1983 and April 26-June 16 in 1984 -- each trap was checked daily, and all captured fish were anaesthetized with MS222, examined for previous fin clips, measured to the nearest millimetre fork length, and sampled for scales. Fish were released below the lowermost trap at the mouth, while fish in the side channel trap were finclipped and released into the Experimental Section to check trapping efficiency. Of 61 such coho released and subsequently recaptured, all were taken by the next trap downstream, indicating that the traps efficiently captured downstream migrants.

# 4 RESULTS AND DISCUSSION

## 4.1 Physical Changes

Planview maps document the channel morphology and LOD test placements at four different times over the study period in Southbay Dump Creek (Figures A1-A4 in the Appendix). On each map the locations indicated for the numbered LOD pieces are the locations of the LOD intentionally placed at each site. Their positions are derived from engineering surveys, while the locations of all other pieces are approximations based on field drawings (with a base map in hand) or low-level aerial photographs (9 m above the stream channel). LOD that was part of a complex debris jam or windrow alongside the valley wall was usually simplified or excluded altogether from the maps, the exception being pieces that clearly influenced the stream channel.

During the study there were many changes in the course of the stream flow and in the amount and type of fish rearing habitat present. Initially, most of these changes were the result of the debris placement operation itself, when pools were either dammed up behind the LOD placements (Sites A, E, F, and L) or dug out of the side channel (Sites I and J). All of these pools, with the exception of Site J on the side channel, filled in rapidly during the first few winter storms. At the same time, however, new pools were also created as sediments were scoured out below, underneath, or alongside the debris. This scouring action continued in succeeding storms, but was complicated because of two unforeseen factors: an increase in the amount of woody debris in the stream and an increase in the amount of sediments.

Most of the extra debris consisted of small material that would have been transported out of Southbay Dump Creek had it not precipitated out behind the LOD emplacements, increasing both the extent of the scouring at each test site as well as its overall complexity. The remainder included large logs and rootwads that had originally been buried by the torrent, but which were uncovered at test sites as a result of increased local scouring. This newly exposed LOD resulted in even further increases in the amount of scour at each test site.

The sediments initially precipitated out behind each LOD emplacement were derived partly from the normal bedload being carried downstream from above the study area, and partly from the extra material being scoured out around the new LOD. The largest increase in sediments in the stream, however, occurred during the torrent-like flood on August 2, 1983, an event that filled virtually every pool in the Experimental Section above Site C with gravel, up to 2 m deep in some cases. Elsewhere, in both the Control and Experimental section below Site C pools were lost not only because of filling, but because riffles between pools were also scoured out. Overall, the bed level of riffle habitats between Sites A and C dropped 0.25 m as a result of the August flood, while increasing by 0.36 m above Site C. The exact source of the excess sediments is not precisely known, but most are believed to be derived from sediments that passed through a recent break in the 9 m high debris jam located 400 m upstream of the study area. Undoubtedly other sediments temporarily stored in gravel bars in the upper portion of the study area also contributed.

The thalweg profile for the Experimental Section showed considerably more variability after LOD was re-introduced (Figure 3). Before introducing LOD, there were only four small pools in the Experimental Section. This increased to 12 as a direct result of the LOD placements, and thereafter to 18 after one winter, the result of localized scouring at each test site (Table 1). The August torrent obliterated most pool habitat formed to that point. While a total of 13 recognizable pools still remained, they were all considerably smaller and more shallow than before. By the end of the second winter, the number of pools had again increased, this time to a high of 21. By comparison, the Control Section had fewer changes over the same period, starting out with a total of eight pools and ending up with seven. Glides, characterizedby smooth, even laminar flows and depths midway between pools and riffles, similarly increased from one to eleven over the period of study in the Experimental Section, but stayed constant at four in the Control Section.

The LOD test placements increased the diversity of pool types in the Experimental Section (Table 1). Before the study began, lateral scour pools predominated. While there was also a plunge pool formed by logs lying across the stream, in most cases what little debris there was in the stream was usually parallel to the main flow on the side of the channel. Using the terminology of Bisson *et al.* (1982), the test placements (primarily cross-stream placements) created not only more lateral scour

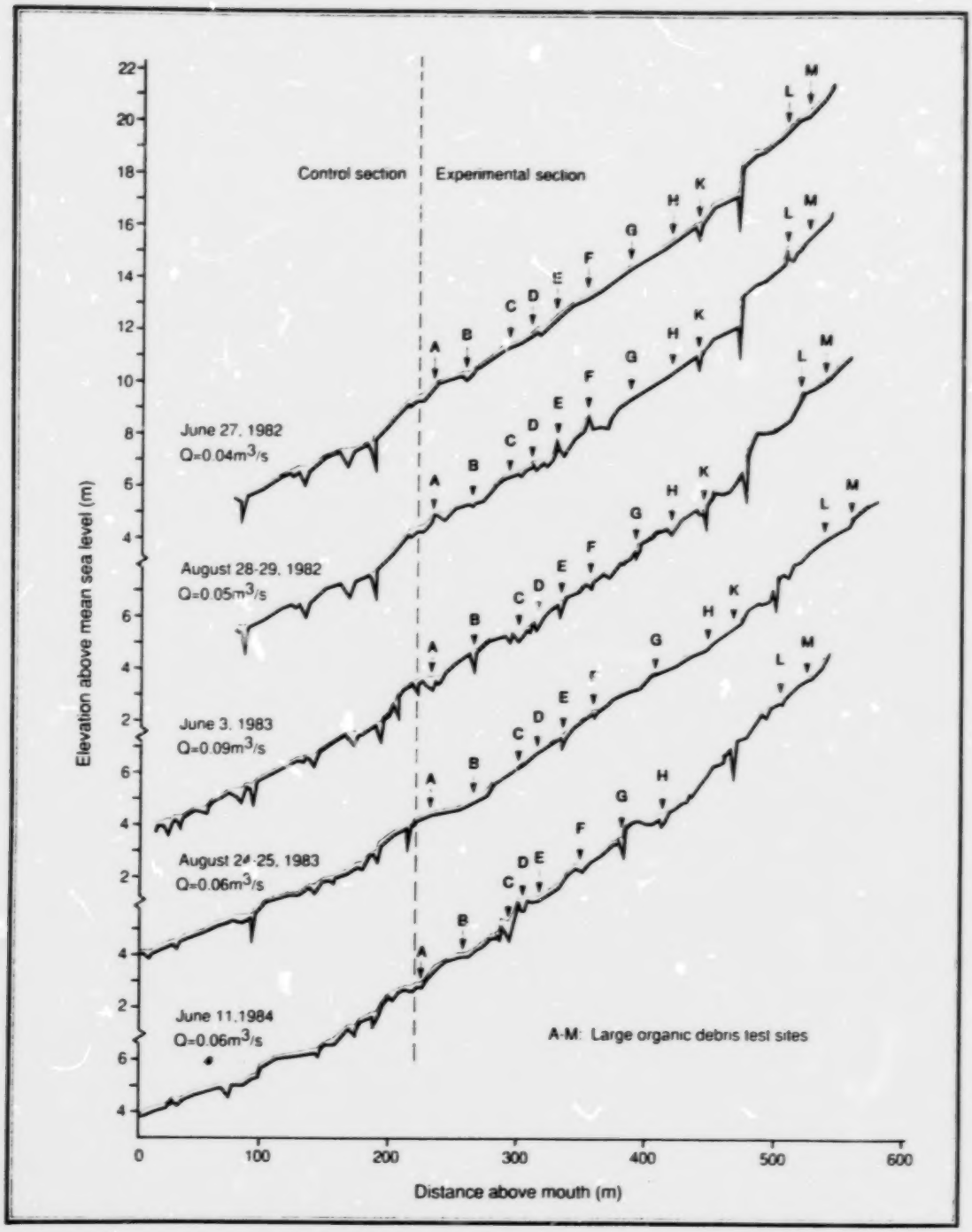


FIGURE 3. Thalweg profiles of the Control and Experimental sections during low flow periods, June 1982 to July 1984.

TABLE 1. Pool number and diversity in the Control and Experimental sections of Southbay Dump Creek, June 1982 to July 1984.

| Date | Pool Type: Lateral Scour | Plunge | Under Scour | Back Water | Dammed | Trench | Side | Total No. Pools | Total No. Pool Types |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Control Section | | | | | |
| June 1982 (Pre-placement) | 6 | 1 | 0 | 0 | 0 | 0 | 1 | 8 | 3 |
| June 1983 (1 winter, post-placement) | 6 | 2 | 0 | 0 | 0 | 0 | 1 | 9 | 3 |
| August 1983 (post summer flood) | 4 | 2 | 0 | 0 | 0 | 0 | 1 | 7 | 3 |
| July 1984 (2 winters post-placement) | 6 | 0 | 0 | 0 | 0 | 0 | 1 | 7 | 3 |
| | | | | Experimental Section | | | | | |
| June 1982 (Pre-placement) | 2 | 1 | 0 | 0 | 0 | 0 | 1 | 4 | 3 |
| August 1982 (Placement) | 3 | 2 | 0 | 0 | 4 | 0 | 3 | 12 | 4 |
| June 1983 (1 winter, post-placement) | 4 | 2 | 5 | 4 | 0 | 0 | 3 | 18 | 5 |
| August 1984 (post summer flood) | 4 | 1 | 1 | 4 | 0 | 0 | 3 | 13 | 5 |
| July 1984 (2 winters, post-placement) | 7 | 8 | 0 | 3 | 1 | 1 | 1 | 21 | 6 |

pools, but also more plunge pools, backwater pools, secondary side channel pools, dammed pools, and trench pools. Cross-stream obstructions also created underscour pools, which were formed as a result of water being deflected underneath the LOD, and LOD "plugged" or "capped" side channel pools, which were formed when debris and sediments plugged up the channel behind the log, forcing the stream to shift its course.

Total pool area in the Experimental Section increased from 2.5% of wetted stream area before the study began, to 18.3% after one winter and 15.4% after the August torrent and a second winter (Figure 4). By comparison, total pool area changed very little in the Control Section other than during the August 1983 torrent pools were filled in. Starting at 16.8% of the total wetted stream area, total pool area was 18.4 and 14.4% after one and two winters, respectively. Total LOD cover also remained stable in the Control Section, ranging from 6.4% of the wetted stream area before the study began, to 6.9% after one year, and 8.2% after two years. In the Experimental Section, LOD cover increased from 2.2% of total wetted stream area to 11.2 and 17.7% after one and two winters, respectively (Figure 5).

Because they spanned more of the stream channel and thus were less likely to be isolated by a shift in the channel, LOD structures oriented across the stream were clearly more effective in creating new habitats than either the oblique configurations or the side channel pools (Table 2). Of the seven LOD test sites with cross-section obstructions, for example, six were still affecting the stream after two winters, although at Site D the log no longer spanned the stream at its original site, but was shifted downstream and wedged across the stream against the log at Site C. Site B, the only cross-stream obstruction no longer directly influencing the stream channel at the end of the study, was still in its original position, but the streambed had degraded to a point where the log was now suspended above the stream.

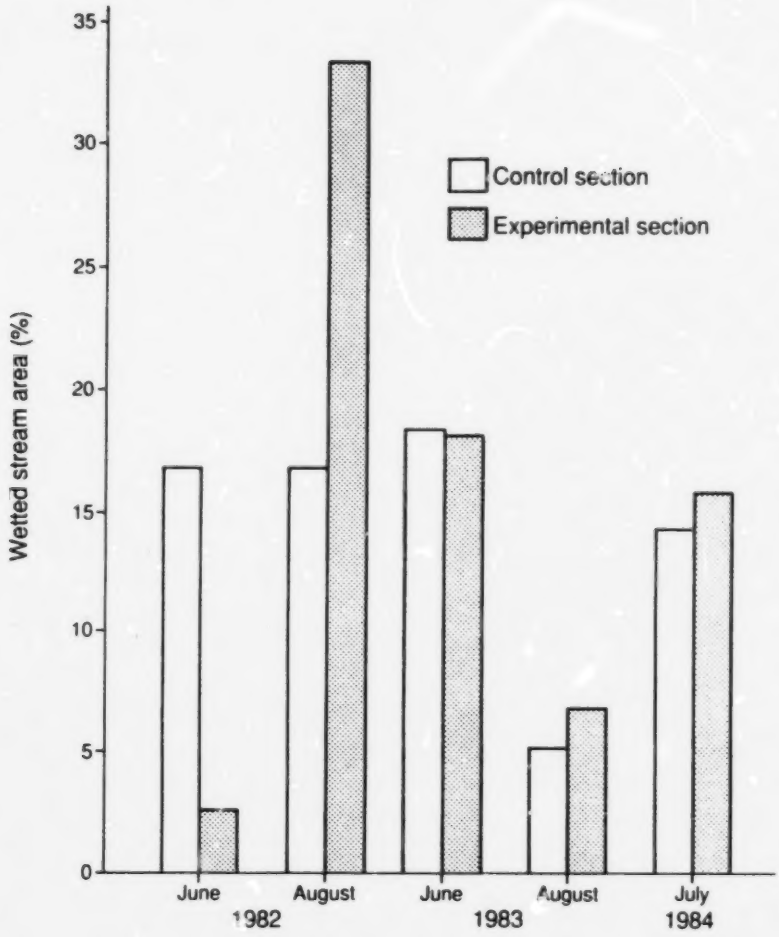


FIGURE 4. Pool area (percent of wetted stream area) in Southbay Dump Creek, June 1982 to July 1984.

Of the four test sites with oblique LOD configurations, only two (Sites A and K) were effective in creating new pool habitat after one winter, and none were effective after two winters. At three sites (Sites K, L, and M), the debris placements were rendered ineffective when the stream shifted its course and isolated the oblique debris placements alongside the valley wall where the stream originally flowed. At the last site (Site A), the two logs originally cabled together into a V-shaped pattern were forced apart and isolated on the floodplain parallel to the stream channel. Of the two side channel pools, Site I was filled in the first winter when flood waters overtopped the low-lying intervening gravel bar separating the side channel and mainstem. Site J, the uppermost side channel pool was filled in by the August 2, 1983 torrent.

Average pool area and maximum pool depth at cross-stream configurations was 14.8 $m^2$ and 0.39 m, respectively, after one winter; and 14.6$m^2$ and 0.44 m after two winters and a summer flood (Table 2). By comparison, pool area and pool depth at oblique configurations averaged only 9.5 $m^2$ and 0.32 m respectively, after one winter, with no pool area after two winters and an average depth of only 0.19 m.

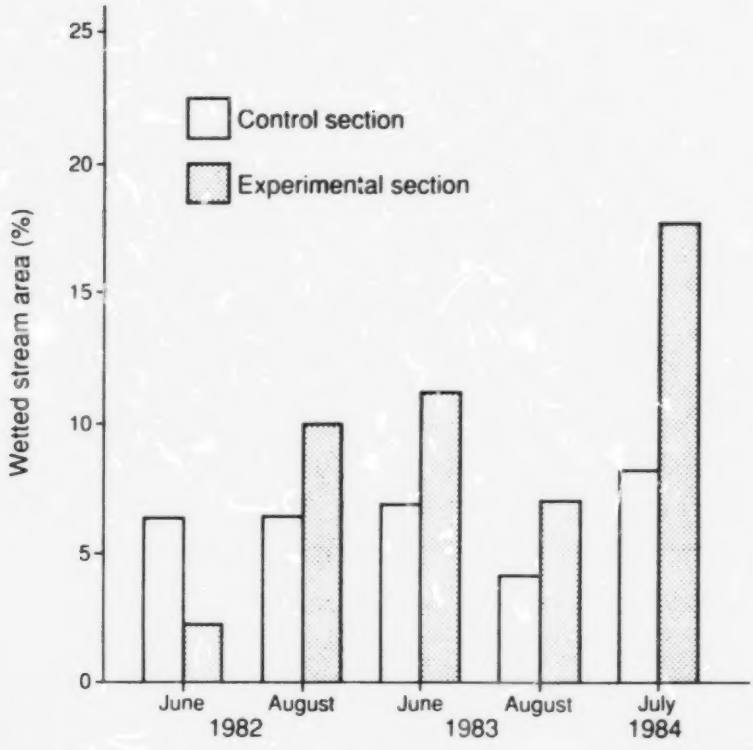


FIGURE 5. LOD cover (percent of wetted stream area) in Southbay Dump Creek, June 1982 to July 1984.

LOD cover at cross-stream sites increased from less than 0.1 $m^2$ per site before the study, to 7.7 and 11.3 $m^2$ per site after one and two winters, respectively, for an average percent pool coverage of 52 and 77%, respectively. A similar increase from 0.8 to 8.3 $m^2$ per site (87% pool coverage) was recorded for the oblique configurations after one winter, dropping back to 0.8 $m^2$ per site after two winters.

Most of the LOD test structures remained more or less in place during the study, with only minor shifts in elevation or orientation, until the last torrent in 1985 after the study was completed. Two exceptions noted earlier included Site D, which eventually ended up against Site C after the 1983 summer torrent, and Site A, where two logs cabled together to a tree and a stump on the banks were pushed apart and isolated on the floodplain, parallel to stream flows. Other major changes caused by the August flood included the LOD at Site I (a side channel pool) wedging against the large rootwad at Site H, 12-15 m downstream, and the main log at Site K twisting 150° so that it now pointed downstream rather than upstream. The logs cabled at each end to trees on the banks at Sites E and F also shifted downstream 2-3 m, because of slack in the cable.

The debris torrent that occurred in the spring of 1985 caused extensive damage throughout the study area, but because it occurred after the study was completed, the changes were not recorded. Brief observations in the fall of 1985 indicated that the only LOD structures still in place and functioning were logs that had been cabled to trees and stumps at Sites A, E, and F. All other sites were either buried or swept away by the force of the torrent. Even the heaviest log, estimated to weigh approximately 20 tons (Site C), had been pushed aside. Where once this log crossed the entire stream channel, it now lay against and parallel to the adjacent valley wall, 5-10 m downstream of its original position.

TABLE 2. Mean pool area, maximum depth, and LOD cover (± 1 SD) at LOD test sites in Southbay Dump Creek, June 1983 (one year post-placement) and July 1984 (two years post-placement)

| Site type | No. sites installed | No. sites still effective | Pool area created ($m^2$) | Maximum stream depth (m) | LOD cover provided ($m^2$) |
|---|---|---|---|---|---|
| | | | June, 1983 | | |
| Cross-stream LOD placements | 7 | 7 | 14.8± 8.5 | 0.39± 0.15 | 7.7± 5.7 |
| Oblique LOD placements | 4 | 3 | 9.5± 9.0 | 0.32± 0.19 | 8.3± 3.8 |
| Side pools | 2 | 1 | 7.0± 9.9 | 0.28± 0.31 | 5.3± 0.6 |
| | | | July, 1984 | | |
| Cross-stream LOD placements | 7 | 6 | 14.6±16.4 | 0.44± 0.19 | 11.3±10.4 |
| Oblique LOD placements | 4 | 0 | 0.0± 0.0 | 0.19± 0.13 | 0.8± 1.0 |
| Side pools | 2 | 0 | 0.0± 0.0 | 0.11± 0.02 | 0.3± 0.4 |

At Site A, the two logs cabled together were stretched across the stream channel and piled high with debris and sediment from upstream. The resulting debris jam completely blocked off the original channel and forced the stream to back up and flow around the jam in an S-shaped pattern through another small jam on the side. Site E had also accumulated a 2 m high pile of debris and sediment upstream so that the stream flowed around one end of the log. The banks at both ends of the jam exhibited considerable erosion, which was undesirable, but it also caused several trees to fall into the stream, thereby contributing to the overall complexity of the site. In many respects Sites A and E both looked like many of the small jams found in non-torrented logged streams: a lot of debris and sediment stored on the upstream side of the jam, and a diverse assortment of LOD-controlled lateral, backwater, plunge, and "capped" side channel pool habitats on the downstream side. Site F, the last site still in place, showed the fewest changes, possibly because with a diameter of only 0.4 m it was also the smallest log. Sediments had filled in upstream while the stream flowed around and then down the face of the log downstream, forming small lateral scour pools in the process.

### 4.2 Coho Survival and Smolt Production

Overwinter coho survival after one winter in the Experimental Section (52%) showed a four-fold increase over survival in the Control Section (13%) (Table 3). This represented an overall smolt yield per unit of stream length that was only slightly lower than the average yield (1.44 fish per metre) in small (<l0 km long) non-torrented streams elsewhere in the Pacific Northwest (Holtby and Hartman 1982). In the Control Section, the average coho smolt yield was 0.28 fish per metre of stream the first year compared to 1.10 fish per metre in the Experimental Section (Figure 6). Since two of the oblique configurations (Sites L and M) never successfully formed or maintained any new pool area, even higher values (57.5% survival and 1.38 fish per metre smolt yield) result when these two sites (located in the upper 65-75 m of the study area) are eliminated. If fish from the highly productive side channel sites are also eliminated, however, slightly lower values result (44.6% survival and 1.07 fish per metre smolt yield).

Overwinter survival and smolt yield in the Experimental Section were substantially lower the second winter, probably because most of the overwinter habitat formed the first winter was eliminated when sediments carried downstream during the August flood filled in most of the pools. Although new pools were eventually formed by the end of the second winter, presumably they were created too late to be of major use to fish. In the Control Section, overwinter survival in 1983/1984 was 15.7%, slightly higher than the previous year, but the smolt yield was only 0.18 fish per metre. In the

TABLE 3. Coho growth, abundance, and survival in the Control and Experimental sections of Southbay Dump Creek, fall 1982 to spring 1984. ND=No Data

| Stream Section | Mean fork length (mm, ±95% C.L.) Fall pre-smolts | Smolts | Spring residuals | Abundance N Fall pre-smolts | Smolts | Spring residuals | % Overwinter Survival |
|---|---|---|---|---|---|---|---|
| | | | 1982 - 1983 | | | | |
| Control | 65.6±2.8 | 89.4±2.1 | ND | 471 | 58 | 5 | 13.4 |
| Experimental | | | | | | | |
| Mainstem | 68.8±1.9 | 91.5±1.3 | ND | 724 | 243 | 13 | 35.4 |
| Side channel | ND | 81.3±1.7 | 73.0±1.7 | 0 | 89 | 28 | ND |
| Mainstem and side channel combined | 68.8±1.9 | ND | ND | 724 | 332 | 41 | 51.5 |
| | | | 1983 - 1984 | | | | |
| Control | 69.2±1.7 | 96.5±3.6 | ND | 272 | 40 | 4 | 16.2 |
| Experimental | | | | | | | |
| Mainstem | 66.7±1.8 | 100.5±4.3 | ND | 437 | 22 | 2 | 5.5 |
| Side channel | 62.7±2.5 | 87.0±5.6 | ND | 129 | 22 | 10 | 24.8 |
| Mainstem and side channel combined | ND | ND | ND | 566 | 44 | 12 | 9.9 |

Experimental Section, survival was 9.9% and smolt yield 0.14 fish per metre. Again, survival and smolt yield were higher (18.0%, 0.34 fish per metre) if only those structures still effective at the end of winter (Sites C to H) are considered, but lower (7.7%, 0.17 fish per metre) if fish from the side channel are also eliminated. By comparison, coho survivals in torrented streams lacking new LOD were only 1-2% the second winter, and 15-36% in non-torrented, logged streams (Tripp and Poulin 1986b).

Neither the age composition nor size of the coho smolts emigrating from the mainstream portions of the Control or Experimental sections of Southbay Dump Creek differed significantly ($P<0.05$) (Table 4, Figure 6). Likewise the proportion of the total coho population remaining behind for a second season in each stream section was also similar. In 1983, 92 and 95% of the coho that successfully overwintered in the mainstem portions of the Control and Experimental sections emigrated as relatively large smolts at an average fork length of 89.4 and 91.5 mm, respectively. Of these, 98% were one-year-old fish. In 1984, 91 and 92% of the surviving coho emigrated from the same stream sections at average fork lengths of 96.5 and 102.5 mm, respectively, 90% of which were one-year-old fish. Proportionately fewer fish emigrated from the experimental side channel pools (69-76%) and at a significantly ($P<0.05$) smaller size (81.3 mm fork length in 1983, 87.0 mm in 1984) than those in the main stream. All were one-year-old fish.

As indicated earlier, oblique configurations where the LOD was set diagonally across a portion of the rooted stream channel were not successful in creating new rearing areas for coho fry. For the most part, this occurred because these sites tended to be easily isolated by relatively small shifts in the streambed. Because they spanned a greater portion of the channel, being isolated was not as serious a problem with the cross-stream configurations, which were highly successful in increasing the amount of rearing habitat available. During the first year at least (1983), this increase in the amount of rearing habitat available in the Experimental Section resulted in corresponding increases in coho fry densities. For example, where pre-treatment 1982 densities (per lineal metre) at cross-stream sites were the same or lower than those at similar riffle sites elsewhere in the Control or Experimental Sections (0.9-1.7 fish per metre, Table 4), 1983 densities (26.3-30.8 fish per metre) were 15-46 times higher than in riffles in the Experimental Section ($P<0.05$). They were also 66-103 times higher than riffle densities in the Control Section. Similarly, while pre-treatment coho densities at cross-stream sites in 1982 were about 3.5 times lower than those in Control Section pools, they were 2.5-2.8 times higher in 1983 ($P<0.05$ in June). Part of the reason for the differences between

TABLE 4. Juvenile coho densities (number of fish per metre of stream length) at pools, riffles, and LOD test sites in the Control and Experimental sections of Southbay Dump Creek August 26, 1982 to July 13, 1984

| Habitat feature | Sample period | | | |
|---|---|---|---|---|
| | Aug 26-Sept 7 1982 | June 9-13 1983 | Sept 12-14 1983 | July 13 1984 |
| Control section | | | | |
| Riffles | 1.7 (1.5-2.0) | 0.3 (0.1-0.7) | 0.4 (0.1-1.1) | 0.1 (0.0-0.5) |
| Pools | 3.4 (3.1-3.7) | 12.1 (7.1-16.9) | 8.1 (3.2-13.0) | 1.0 (0.5-2.3) |
| Experimental section | | | | |
| Riffles | 0.9 (0.7-1.1) | 1.8 (1.3-3.0) | 0.5 (0.3-1.2) | 0.1 (0.0-0.3) |
| Pools | 3.3 (2.5-5.0) | 26.9 (14.9-38.9) | 23.0 (11.6-34.4) | 0.6 (0.4-1.3) |
| Cross-stream LOD sites | 1.0 (0.8-1.2) | 30.8 (19.9-41.7) | 26.3 (8.7-43.9) | 0.6 (0.2-1.2) |
| Oblique LOD sites | 1.2 (0.8-1.9) | 2.5 (2.0-3.6) | 0.7 (0.3-2.4) | 0.1 (0.0-0.4) |

Numbers in brackets are 95% confidence limits.

pool densities in the Control Section and at cross stream sites is that pools formed at the cross-stream sites tended to be wider, deeper, and more intimately associated with LOD. Like pools at oblique LOD sites, pools in the Control Section tended to be lateral-scour pools, whereas those at cross-stream sites tended to be backwater, plunge, underscour, or LOD "capped" side channel pools.

Coho fry densities were very low in July, 1984 (0.1 fish per metre in riffles and 0.6-1.0 fish per metre in pools, Table 4), and clearly unrelated to the amount of pool habitat present in either the Control or Experimental sections. Although reasons for the low densities are not definitely known, they are believed to be largely the result of excess gravel scouring over winter and not to differences in the number of spawners or high sediment levels. During the 1983-1984 winter period, the average depth of gravel scour recorded at pool/riffle boundaries in Southbay Dump Creek was 35 cm (Tripp and Poulin 1986c) for an estimated egg loss of 82% from scouring alone. Some of this scouring was triggered by the LOD placements themselves, in combination with the extra sediments deposited earlier by the August 2 flood. However, equally high levels of scouring in other nearby torrented streams suggests that the new LOD in Southbay Dump Creek was not a critical factor.

### 4.3 Benefit/Cost Relationships

The overall average cost per LOD structure, excluding equipment transportation costs to the study area, was $84.50 (Can.), ranging from $46 for the two side channel sites which took only 20-25 minutes each to build, to $92 and $109 for the oblique and cross-stream structures which averaged 45 and 55 minutes to build, respectively (Table 5). Depending on the complexity of the structure,

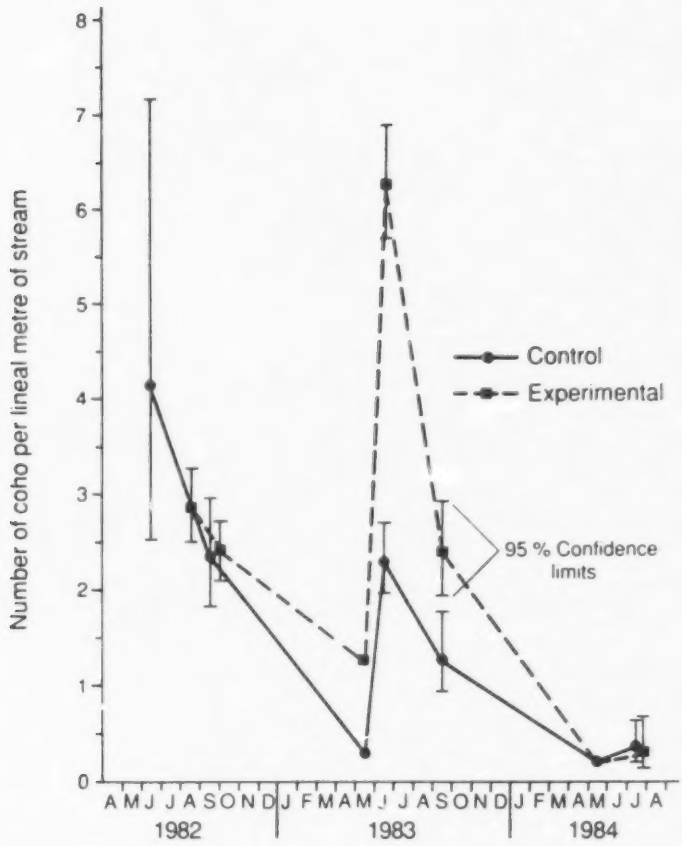


FIGURE 6. Juvenile coho densities in the Control and Experimental sections of Southbay Dump Creek.

construction time was as brief as 10 minutes if LOD was readily accessible nearby and simply lifted or dragged into the stream and left (e.g., Sites B and M). At other sites where additional logs were dragged up from the estuary (a one-hour job) and cabled into place after a shallow trench was excavated and backfilled (Sites E and F), construction time was as long as 90 minutes.

Total cost of the LOD placements in Southbay Dump Creek was $1720 (1982 dollars; Table 6), including $1100 for 10 hours of FMC log skidder time (complete with an operator) to acquire and place the LOD, and $120 for an assistant to handle the choker lines, cable the necessary logs, and aid in the placement of the LOD. Other costs included $500, a flat fee charged by the contractor for transporting the skidder to the study site from Rennell Sound on the west coast of Graham Island, a distance of approximately 70 km. There were no costs associated with the LOD itself, which was simply logs and rootwads piled up alongside the valley walls by the debris torrent or washed up on the estuary. There were also no costs for the cable,which had been abandoned nearby, or for other equipment used (i.e., chainsaws, cable cutters, handtools), included in the cost of the skidder.

The long-term cost-effectiveness of putting LOD back into debris torrented streams was estimated by assuming that the number of extra coho smolts produced the first year in the Experimental would be forthcoming every year, and that the benefits derived from the extra adults ultimately produced would start accumulating two years later when the first smolts mature. Survival from the smolt stage to the adult stage was assumed to be 15% (Salmonid Enhancement Program bioengineering standards), while the average net wholesale value of an adult coho in 1982 dollars was assumed to be $15.48. Inasmuch as there is no major sport fishery on the north coast yet, the latter

TABLE 5. Average placement time and costs for the different LOD configurations tested in Southbay Dump, exclusive of costs for transporting heavy equipment to the Study Area

| Test site type | Average placement time (min.) | Average placement cost ($) | Work involved |
|---|---|---|---|
| Cross-stream LOD placements (N=7) | 55 | 108.90 | Four logs picked up at estuary for 3 sites, LOD placed at 7 sites, excavation and infilling at 4 sites, logs cabled at 3 sites |
| Oblique LOD placements (N=4) | 45 | 91.50 | LOD placed at 4 sites, excavation and infilling at 2 sites, logs cabled at 1 site |
| Side-channel sites (N=2) | 23 | 45.75 | Pools excavated at both sites, LOD placed at both sites |
| All sites (N=13) | 46 | 84.50 | All of the above |

TABLE 6. Summary of the benefits and costs of replacing LOD in the Experimental Section of Southbay Dump Creek

| Benefit/Costs (1982 Dollars) | All mainstem and side channel sites | Effective mainstem and side channel sites | Effective mainstem sites only |
|---|---|---|---|
| **Costs** | | | |
| Equipment transport | $ 500.00 | $ 500.00 | $ 500.00 |
| Skidder rental (FMC - $110/hr) | $1,100.00 | $ 852.50 | $ 797.50 |
| Labour ($12/hr) | $ 120.00 | $ 93.00 | $ 87.00 |
| Total | $1,720.00 | $1,445.50 | $1,384.50 |
| **Benefits** | | | |
| Extra coho smolts produced | 274 | 274 | 185 |
| Extra coho adults produced | 41 | 41 | 28 |
| Adult net wholesale value | $ 15.38 | $ 15.38 | $ 15.38 |
| Accumulated benefits in 10 years | $3,136.56 | $3,136.56 | $2,117.81 |
| Accumulated benefits in 20 years | $4,428.57 | $4,428.57 | $2,990.27 |
| **Benefit/Cost ratios** | | | |
| 10 years | 1.83:1 | 2.17:1 | 1.53:1 |
| 20 years | 2.57:1 | 3.06:1 | 2.16:1 |

figure assumes all coho are caught commercially (80% in the troll fishery, 20% in the net fishery), and is based on 1978 net wholesale values ( P. Kopas, pers. comm., Habitat Economist, Dep. Fisheries and Oceans, Vancouver, B.C.) multiplied by a consumer price index of 1.48 to produce 1982 values. Benefits were discounted by 10% annually.

The break-even point where the benefits derived from the extra coho produced equals the cost of putting LOD back into debris-torrented streams appears to be at five or six years (Figure 7), regardless of whether sites that failed to create new habitat were considered or not. For all LOD test placements in Southbay Dump Creek, the benefit/cost ratios based on the first year's survivals were 1.8:1 after 10 years and 2.6:1 after 20 years (Table 6). Eliminating from construction costs the sites that failed to create any new pool habitat (i.e., Sites I, L, and M, Figure 2) increased the benefit/cost ratios to 2.2:1 and 3.1:1 after 10 and 20 years; eliminating production from the side channel lowered the ratios (to 1.5:1 and 2.2:1, respectively).

The benefit/cost analysis indicated that restoring LOD back into debris-torrented streams is a promising technique, potentially as cost-effective as hatcheries or other stream enhancement techniques, such as placing boulders in clusters (see Ward and Slaney 1979), provided there is no more mass wasting. Under these conditions the analysis is believed to be a conservative estimate of the true cost-effectiveness, because it accounts only for benefits to the commercial coho fishery. Benefits accruing to a sport fishery are likely to be substantially higher, especially if steelhead, a much more valuable sport fish, are being enhanced as well. Other benefits not included in the analysis are a potential increase in egg-to-fry survivals because of increases in the amount of high-quality spawning habitat created at the tail ends of new pools. While improved egg-to-fry survival is not ordinarily an important factor for the production of coho or steelhead smolts in undisturbed populations where the number of adults returning to spawn is large, it is a critical factor in failing populations where the number of breeding fish is very small or where a greater harvestable surplus is desired. Chum salmon frequently suffer catastrophic losses of spawning habitat in mass-wasted streams, and thus increases in fry production resulting from LOD-related improvements in the quantity and/or quality of spawning habitat available can be important.

Other benefits include a potential increase in the rate at which streams recover from the effects of excessive mass wasting. While the re-establishment of suitable pool/riffle sequences is probably the most important step to fish, full recovery also requires the removal of all excess sediment from the stream channel (Lisle 1981). In debris-torrented streams lacking sufficient LOD, the substrate often has an imbricated appearance that resists further scouring except during major floods. By deflecting flows directly into the substrate, introducing LOD will, in theory, increase the amount of scour at low flow levels and thus the amount of sediment being transported. Also at higher flows, the amount of sediment being removed from the streambed appeared to be increased, possibly because with more sediment precipitating out and being placed in storage behind the LOD placements, more was capable of being picked up below the LOD placements.

Restoration of LOD in debris-torrented streams may also help stimulate revegetation of the banks by improving soil conditions. Whereas the floodplain and streambank surfaces tended to be very coarse, dry, and devoid of vegetation before LOD was added to the stream, after LOD was introduced significant amounts of sand and fine-sized sediments started to accumulate at a number of locations (usually near LOD). Plant growth may improve at such sites, in turn triggering other self-perpetuating processes such as silt and sand deposition away from the wetted channel, further plant growth, and increasing bank stability (Lisle 1981).

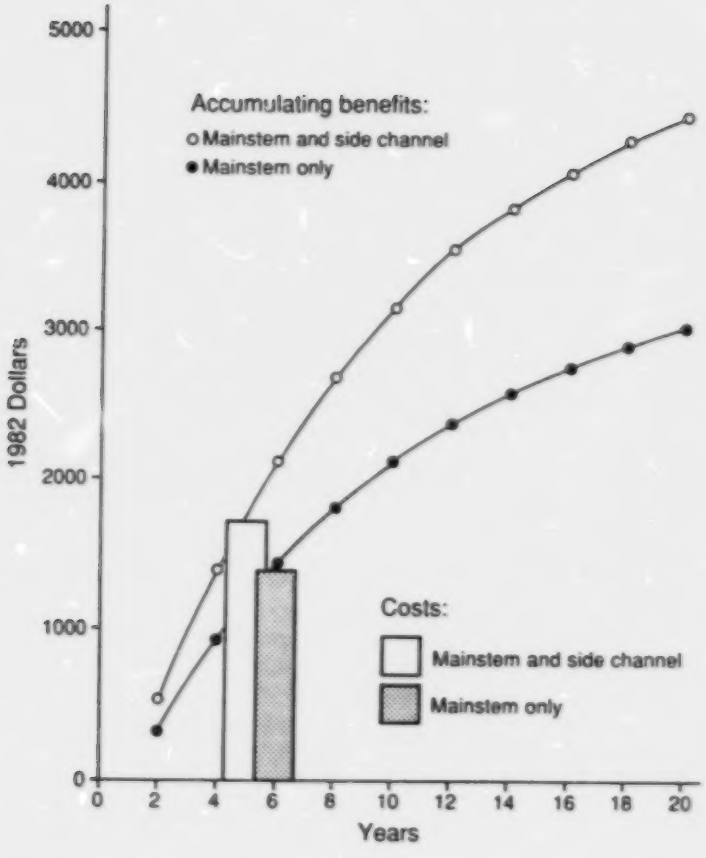


FIGURE 7. Construction costs and accumulated benefits for large organic debris emplacements in Southbay Dump Creek

# 5 GENERAL DISCUSSION

Debris-torrented streams similar to Southbay Dump Creek tend to be simple, channelized systems with long cobble-bedded riffles and small, shallow pools offering little protection to fish from predators or high flows. Because of high bedload movements and a lack of stable hydraulic controls, whatever habitat is available to rearing species (e.g., coho) also tends to be very transient, present one year and gone the next. By adding LOD back into the stream, it was hoped that the natural scouring action of streams around new LOD would increase the number of pools present, and thus the amount of habitat available for rearing juveniles.

That some of the LOD added to Southbay Dump Creek did create new pool habitats was not unexpected. What was surprising was how quickly a complex system of pools, glides, riffles, and side channels developed, and how quickly juvenile coho initially responded to the changes in terms of increased smolt production. No doubt the large volumes of unstored (and therefore mobile) sediment and debris present in the channel were important contributing factors, because it meant that pools could be quickly scoured out below a log, and then quickly complexed with debris and sediment precipitating out above the log. In stable stream reaches with a low bedload, little debris, and a substrate resistant to further scouring, the formation of complex new pool habitats may be much slower, although longer lasting than in rapidly changing systems such as Southbay Dump Creek.

## 5.1 One-Step Versus Two-Step Approaches

At the beginning of the study there was considerable concern that pools formed by structurally very simple arrangements of LOD would not have the complexity necessary to serve as overwintering areas for juvenile salmonids, and that further instream work would be required. A two-step approach was initially thought to be the most cost-effective way of creating new mainstream pools with the characteristics needed to overwinter fish. In the first step, simple arrangements of one or two logs would be added to the stream and then left alone, allowing nature to take its course. In the second step, whatever pools had formed would be complexed further after 1-2 years with additional debris, creating pools with the desired attributes.

This approach is probably effective in stable, low gradient streams where flows, debris, and sediment movements respond in a comparatively simple and predictable manner. Streams subjected to the kind of mass wasting occurring on the Queen Charlotte Islands, however, where entire streams are often sluiced out, are highly unstable and may continue to transport out vast amounts of sediment and debris intermittently for many years. In these streams, waiting until the stream channel settles before initiating mitigative measures to reduce the impacts of mass wasting increases the risk of losing fish populations altogether.

In debris-torrented streams where the rapid downstream flow of sediments and debris can contribute to an equally rapid evolution of pool habitats, a two-stage approach may not be appropriate. Immediate increases in smolt production the first spring after placing LOD in the stream demonstrated that at least some structures were sufficiently complex. Costs aside, in the long run the main intent of restoring LOD in highly unstable streams may simply be to maintain sufficient numbers of fish to act as a nucleus for vigorous self-sustaining populations when conditions eventually destabilize.

## 5.2 LOD Effectiveness and Durability

In stream channels directly affected by debris torrents and other forms of mass wasting, such as slides or excessive bank erosion, there is a high degree of unpredictability regarding: the amount of sediment and debris lying just underneath the surface; the amount that will be transported downstream during major storms; and the amount that will be added from upstream. In such cases, the most effective LOD configuration will be one that continues scouring and precipitating debris and sediment regardless of whether the stream channel shifts its position. In this study, single logs placed perpendicular to the direction of stream flows and crossing as much of the rooted channel as possible were the most effective structures overall. This occurred because they were capable of intercepting the stream regardless of where it shifted laterally in response to debris and sediment

accumulating behind the log. In fact, as long as the test placements remained in place and obstructed stream flows in some way, it was the channel shifting from side to side that helped create the most habitat — plunge pools, underscour pools, backwater pools, lateral scour pools, and LOD "capped" side channel pools. Because they spanned only a small portion of the rooted channel, short, large diameter, diagonal LOD was readily isolated to one side when water flowing under the log was eventually clogged with debris and sediment. Unable to flow over the log, the stream eroded a new channel around the log.

On the west coast, the real test of a stream improvement technique is whether it can survive major storm events long enough for benefits to overcome construction and maintenance costs. In this regard, Southbay Dump Creek was an appropriate test of the long-term durability of LOD placements in small debris-torrented streams. With 81% of its watershed logged, a major debris torrent-like flood in summer 1983, and a full-scale debris torrent in spring 1985, few other streams are likely to have been as active over so short a period. Accordingly, the results indicate that cabling both ends of large logs (>0.5 m in diameter) to secure anchor points on the bank can hold logs in place even during a full-scale debris torrent. Anything less, however, and even the largest debris pieces (in this study, a log 13 m long and 1.4 m in diameter) will probably be swept aside. Under less severe conditions, large logs or rootwads greater than 4 $m^3$ (the average size of pieces tested in this study) were capable of staying more or less in place, owing to their weight during a flood large enough to change the average streambed level by 0.4 m. Interestingly, on the basis of his study on logged and unlogged streams, Hogan (1985) also suggests using only LOD with a volume more than 3 $m^3$ in stream rehabilitation projects. The loss of LOD structures to debris torrents, such as the one after this study, could be avoided if these factors are kept in mind during structure design.

### 5.3 Preliminary Guidelines

While much was learned in this study about the feasibility of using LOD to restore fish habitat in small streams affected by mass wasting, it is too early to recommend anything but very general guidelines for placing LOD in streams. After all, only three out of thirteen sites at this point are still functioning in Southbay Dump Creek, albeit only because of a major debris torrent in the spring of 1985. The study was conducted in a stream reach containing both sediment transport and depositional sites, and the results may be quite different at higher or lower gradients. They may also differ substantially in large streams where the buoyant forces on LOD are greater than those experienced here.

Based on the present study results, the best strategy for replacing LOD in streams in a way that enables structures to withstand debris torrents and create habitat is to:

1. Use single pieces of LOD long and strong enough to intersect as much of the stream channel as possible. In this way, new habitat is scoured out no matter where the stream itself shifts in response to LOD triggered changes in the way channel sediments and debris are transported or stored. A right angle cross-stream configuration is preferred because it does not require as long a log, but there is no compelling reason not to use a diagonal configuration as long as it can span the entire stream channel. Anderson *et al.* (1984) in fact recommend diagonal placements on stream bends, with the upstream end on the inside bend to encourage flows over the structure and away from the outside bend.
2. Cable each end of the logs to secure anchor points on the bank, unless they can be effectively wedged in place within the stream channel. Short, heavy pieces of LOD can also be used. Although easily isolated by small shifts in the channel, they nevertheless remain effective sediment storage sites and should thus be considered an integral part of any rehabilitation program requiring extra sediment storage. Where suitable anchor points on the banks are lacking, "dead man" anchors consisting of logs buried several metres below the streambed should be considered.
3. Place LOD so that it does in fact promote scouring, either flat on the streambed or filled, with one end buried in the streambed and the other end on the bank. With the first configuration, scouring should occur along the entire length of the log over a narrow range of water levels. With the second configuration, scouring should occur at various points along the log over a

wide range of water levels. Where floodplain banks or gravel bars are too high, excavate a trench the length of the log and lower it in place. Backfilling the trench is not necessary, although placing boulders and organic debris on the upstream side would reduce the tendency for the LOD to float, at the same time encouraging further sediment and debris deposition later on. Although again not necessary, short pools could also be dug along the length of the LOD on the downstream side to provide a temporary refuge for juvenile fish until more permanent pools are formed.

The spacing required between LOD placements was not examined in this study. Based on the natural channel morphology of non-torrented unlogged and recently logged Queen Charlotte Island streams, Hogan (1985) recommends spacing LOD two to three channel widths apart, bearing in mind that channel (rooted) widths in debris-torrented streams are almost twice as high as in non-torrented streams (Tripp and Poulin 1986a). When logs with rootwads attached are used, Hogan also recommends placing the rootwad close to the bank and on the downstream end. With rootwads on the upstream end there is a much greater risk of the stream eventually swinging the log parallel to the stream bank.

In this study large-diameter logs were not cabled, as it was expected they would remain in place by virtue of their own weight. By its "operational" nature, the study purposely restricted log use to those readily available nearby. Most of these were large diameter logs because anything smaller tended to be broken up or carried away. Because a lot of the debris consisted of timber used in bridges or for transport on trucks, it also tended to have a fairly standard length, with very few pieces longer than 10-12 m.

The above approach was, for the most part, a successful way of keeping LOD in place in the absence of mass wasting. There are, however, a number of reasons why a more elegant approach using smaller diameter logs is desirable, not the least of which is a reduction in the potential commercial value of the logs. Access to streams, for example, is a frequent problem in many areas, and smaller, more maneuverable ground equipment or helicopters incapable of moving large heavy logs may be all that can be used. In many streams, "large" LOD may not always be available, especially if the best pieces are used up in earlier rehabilitation efforts or where LOD was removed from the stream during logging.

There are other problems associated with using LOD with a diameter greater than, approximately 0.5 m. First, large-diameter logs exert a greater buoyant force than small logs and therefore have a greater chance of being isolated by a shifting stream channel. Unable to flow over the log, the stream is encouraged to erode a new channel around the log when the channel originally flowing underneath the log clogs. Burying and anchoring the log so that the top of the log is lower than the adjacent banks would reduce the risk of the stream shifting position, but at increased cost. Second, too large a log also increases the risk of creating barriers to upstream fish movements. This was especially evident at Site C where, by the end of 1983,sediment and debris accumulating behind the log had completely filled in the stream to the top of the log, a depth of 1.4 m. While water flowing around the log did so in a series of stepped pools, the potential for creating a barrier to upstream fish movements clearly existed, particularly for juvenile fish. Finally, one site (Site C) was highly effective at intercepting sediment, such that it greatly increased the ability of the stream to pick up additional sediment downstream. During floods, this helped to increase scouring downstream to a point where the next 60 m of stream was scoured to an average depth of 0.26 m. The next two LOD sites downstream were stranded as a result, and indicated that sudden decreases in bedload can have as dramatic an effect on the stream morphology as sudden increases. Hence, bedload dynamics is another factor that has to be considered when very large diameter logs are used to rehabilitate a stream.

When an "optimal" configuration for LOD in streams is being decided, one point worth noting is that when the stream was incapable of flowing over a debris placement set on a diagonal, it flowed alongside the log, either on the upstream or downstream side. When a stream flowed over a diagonally positioned log, however, there was a tendency for the stream to continue downstream at right angles to the long axis of the log, as long as the log was not tilted too much, (i.e., one end higher than the other). At such sites the apparent "forward" component of the water flowing downstream appeared to be diminished, but not the "lateral" component.

The same thing happens at gabions (wire mesh baskets filled with rocks) arranged in V-shaped patterns pointing downstream. With this configuration, the result is usually two scour holes, one on each downstream side of the V, with a marked depositional zone immediately below the apex (see also Klassen 1984; Klingeman 1984; House and Boehne 1985). By eroding away at the banks beside the wings of such gabions, the lateral scouring action increases the risks of the gabions breaking away. It also increases the chances of the thalweg shifting from the center of the gabion to one of the two sides, thereby isolating the opposite side and reducing the overall cost-effectiveness of a gabion.

Arch-like structures made out of gabions or logs with the apex of the V pointing upstream may be a more appropriate arrangement than those pointing downstream. Unlike downstream pointing V's, an upstream pointing V should direct flows toward the center of the stream. As a result, the lateral bank erosion usually associated with downstream pointing gabions could be substantially reduced along with the costs of riprapping the banks to reduce erosion. By concentrating flows toward the center of the stream, the structure would also facilitate fish passage above it during low flows, while the amount of pool scouring below the structure would be enhanced at high flows. Properly anchored to prevent floating, arch-like structures should theoretically be stable and difficult to dislodge during major storms or high bedload movements. With the extra strength conferred by arches, such structures also represent a way of spanning the entire width of a stream channel using shorter and lighter logs, and therefore more readily available and economical logs.

# 6 CONCLUSIONS

The results of this study show that by increasing the amount of localized scouring and deposition, relatively simple arrangements of LOD placed in the sediment-rich zones of debris-torrented streams can trigger a rapid development of new pool habitat, sufficiently complex to cause an almost immediate increase in coho overwinter survival and smolt production. As long as there is no further mass wasting, the method also appears to be capable of paying for itself in as little as five or six years, and possibly sooner if other species are benefited. Cabling both ends of a log to secure anchor points will keep most LOD in place and functioning even after a debris torrent; otherwise even the largest logs will probably be swept aside.

Putting LOD back into severely damaged streams is a promising and potentially cost-effective rehabilitation technique that could help offset many of the impacts of mass wasting on fish production, particularly in stream reaches with an abundance of sediments and almost no debris. Before its wide-scale application can be recommended, however, further work is needed on developing durable LOD structures that can accommodate large-scale sediment movements and channel shifts without blocking the stream channel or losing ability to create stable spawning and rearing habitat. To manipulate stream flows more precisely and increase the chances of success, studies are needed on proper spacing, the minimum number of LOD pieces needed per unit stream length,;and how sediment storage/scour characteristics (location, depth, volume) are affected by LOD size and orientation at varying stage levels. The latter studies are best undertaken by hydraulic engineers and fishery biologists working together.

Additional studies should be undertaken in different stream types to assess the effects of different gradients and substrate types. It may be appropriate, for example, to see if the same initial successes obtained in this study can also be obtained in steeper gradient reaches (i.e., those greater than 3-4%). These are the stream reaches most often affected by mass wasting, but because of the coarser substrates present and a species complex dominated by Dolly Varden char and/or cutthroat trout, they are also likely to be much harder to rehabilitate. Adding LOD to lower gradient non-torrented streams also has some merit as an enhancement technique, but here again further study is recommended to see if the method can be cost-effective. Like steep stream reaches, the results in lower gradients may not be as pronounced or as quick as those recorded in this study if there is no extra debris available for complexing new pools. Other factors such as too few breeding fish because of overfishing may be having as great or greater an effect on overall productivity as the amount of rearing habitat available; further improvements to the rearing habitat may be ineffective. In these streams, the best reason for adding new LOD may be to improve egg-to-fry survival by improving gravel quality and stability, capabilities of new LOD that still need to be quantified.

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## APPENDIX

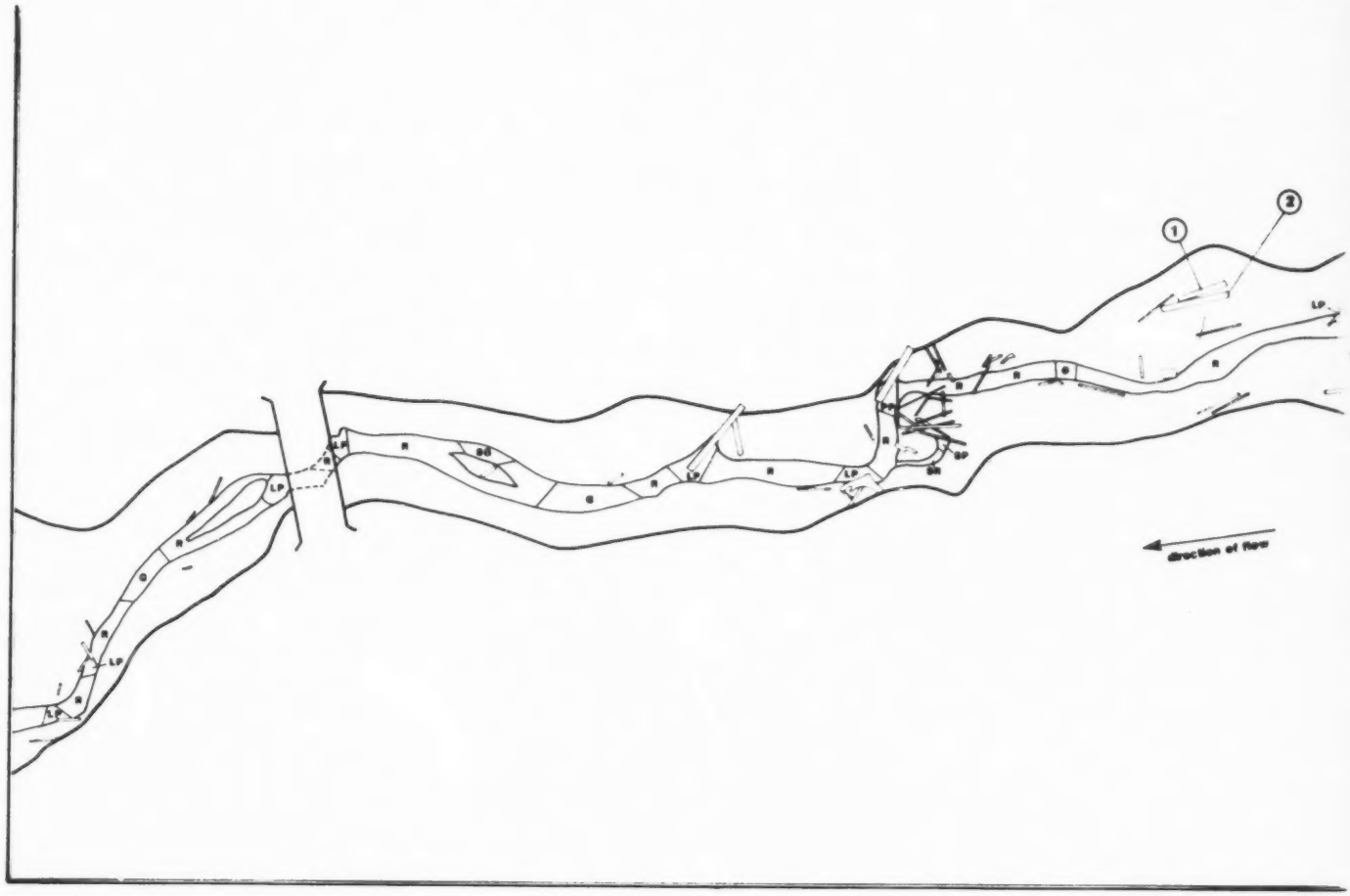
**FIGURES**


Figure A1 Southbay Dump Creek showing subhabitat features before log placement. Date mapped: June 27, 1982. ..... 27

Figure A2 Southbay Dump Creek showing subhabitat features immediately after log placement. Date mapped: August 28 and 29, 1982. ..... 27

Figure A3 Southbay Dump Creek showing subhabitat features 10 months after log placement. Date mapped: June 3, 1983. ..... 28

Figure A4 Southbay Dump Creek showing subhabitat features 12 months after log placement. Date mapped: August 24 and 25, 1983. ..... 28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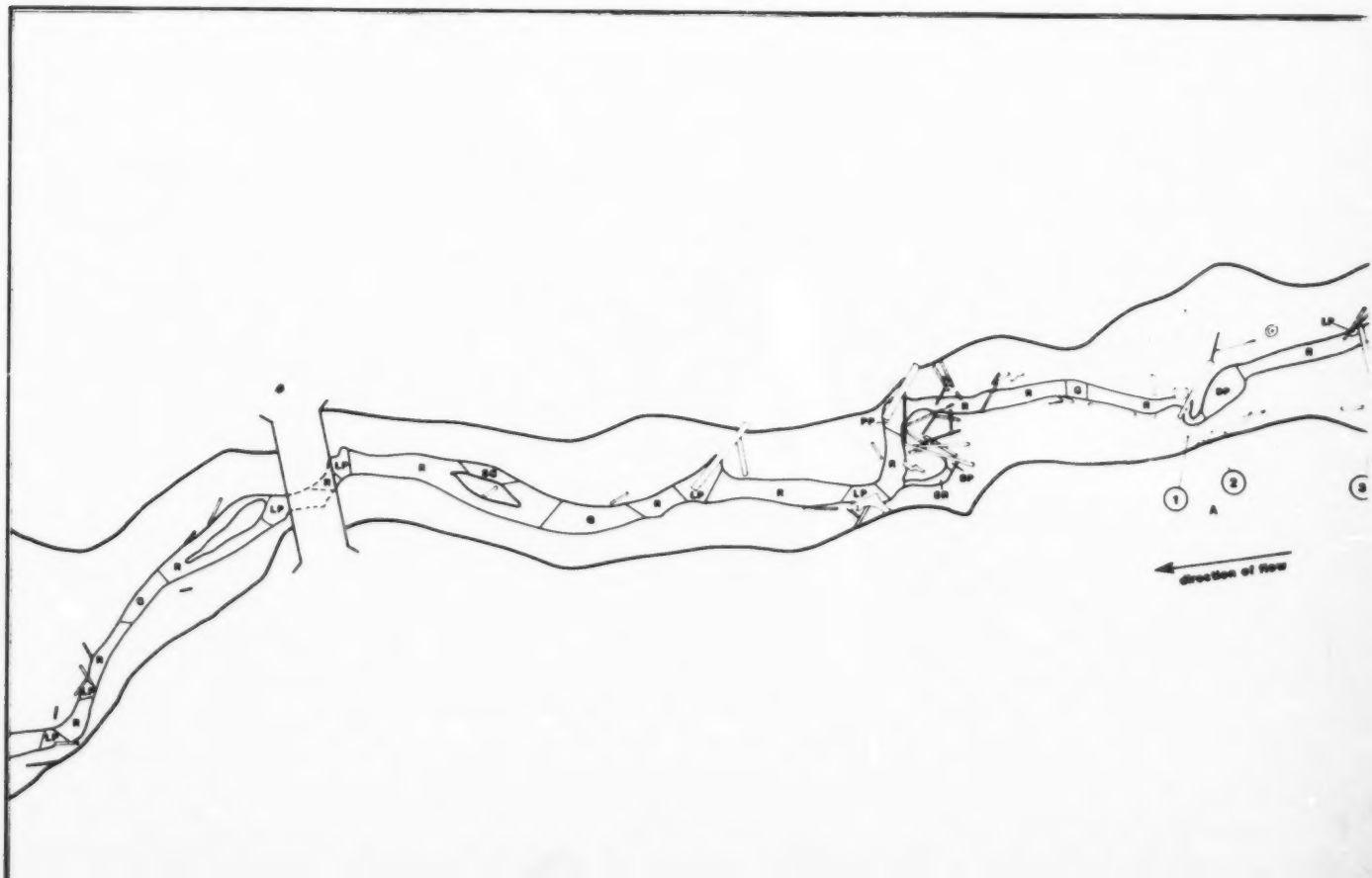
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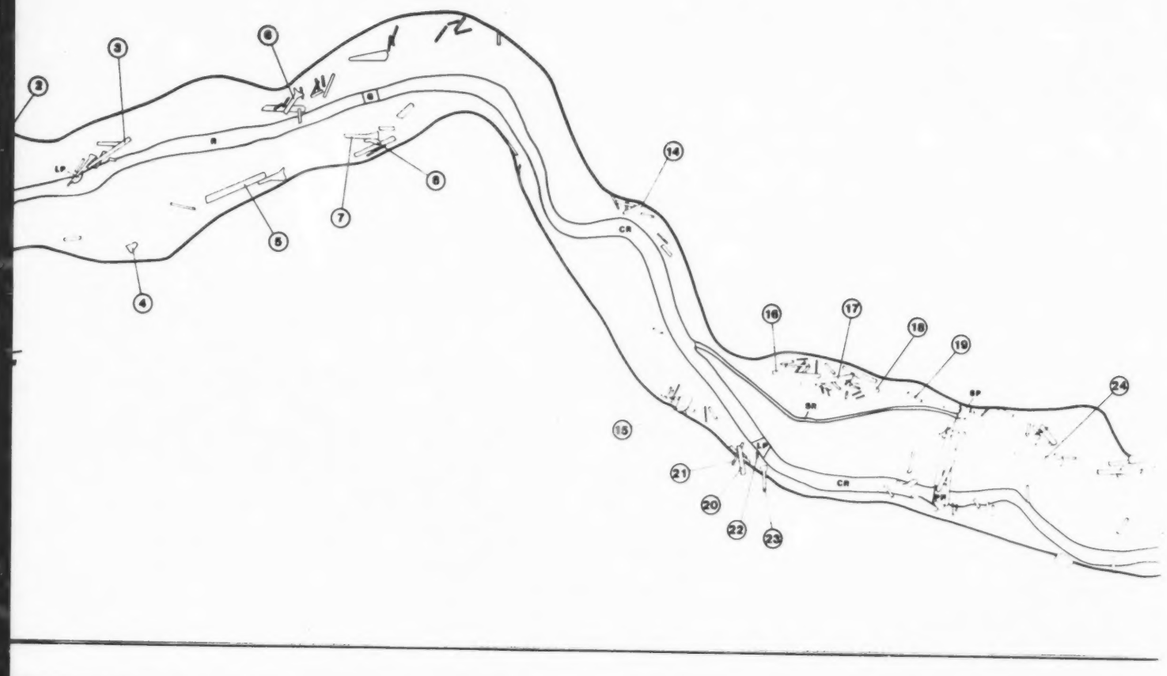


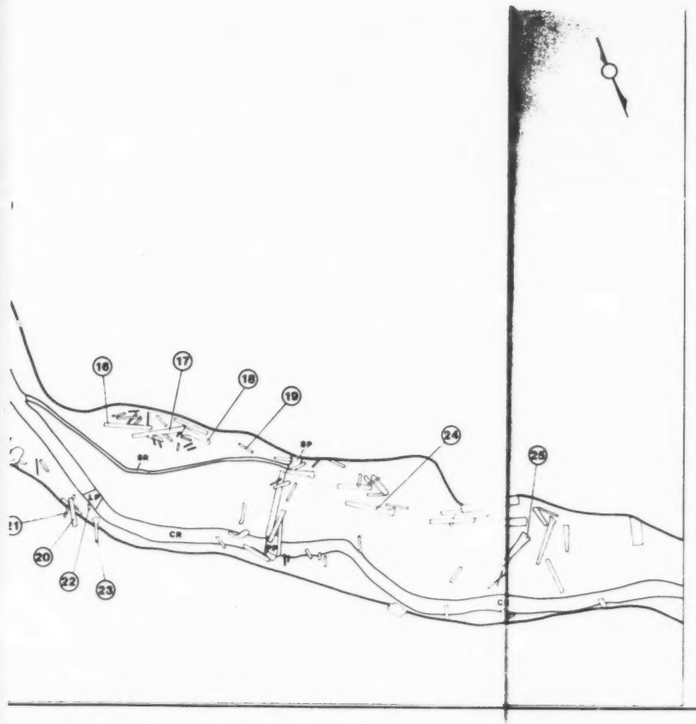




**FIGURE A1: Southbay Dump Creek showing subhabitat features before log placement. Date mapped June 27, 1982. Stream discharge = 0.04 $m^3/s$**

SCALE

0 5 10 15 metres

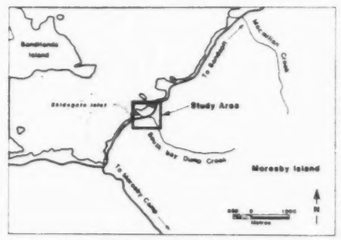
LEGEND

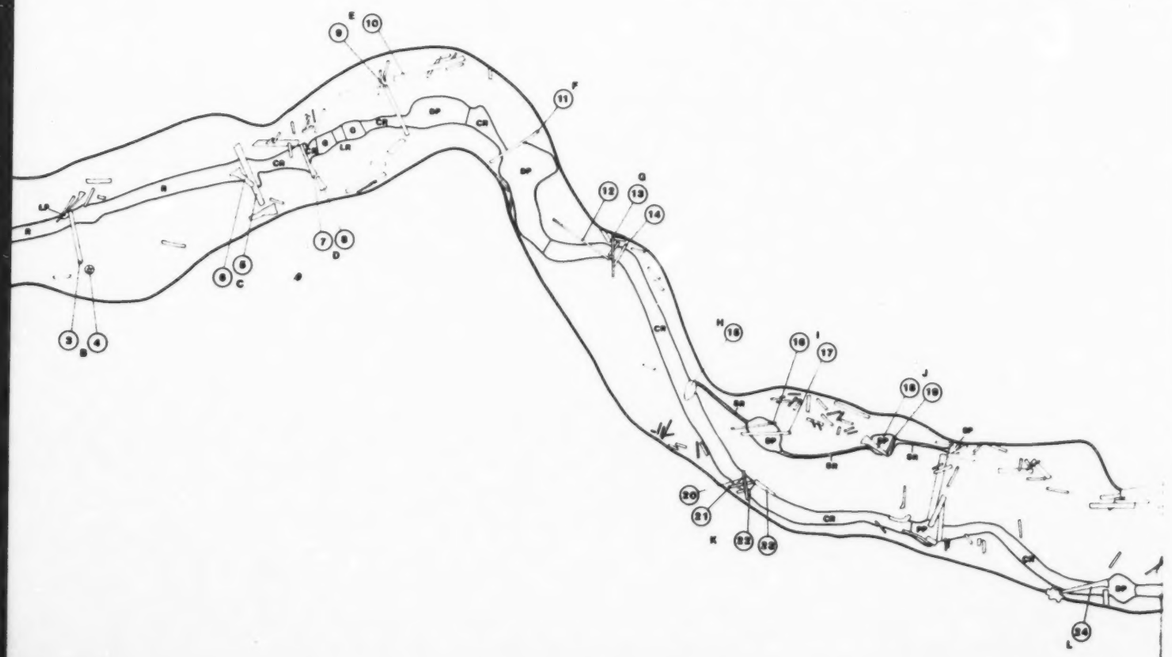
STREAM HABITATS

| | | | |
|---|---|---|---|
| LP | lateral scour pool | SP | side channel pool |
| PP | plunge pool | G | glide |
| DP | dammed pool | R | riffle |
| BP | backwater pool | CR | cascade riffle |
| UP | undercour pool | | |

① debris pieces moved to test sites (August 16-18, 1982)

Ⓐ location of test sites



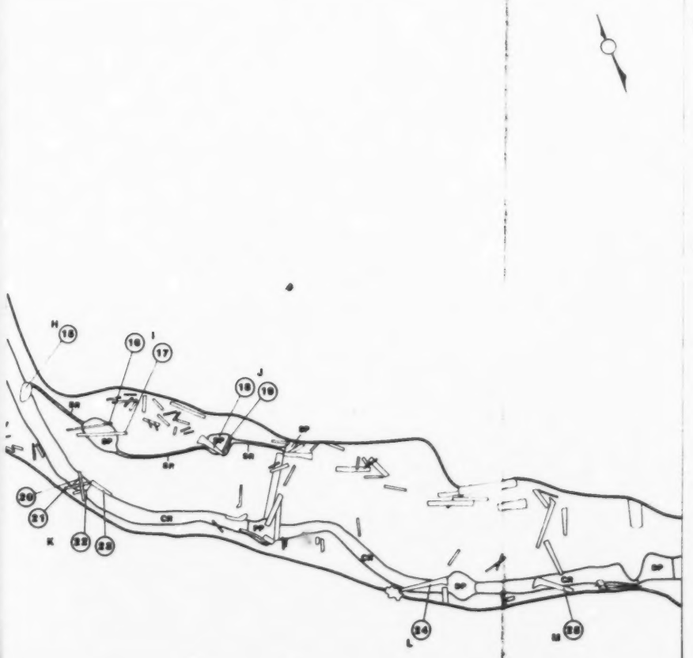




**FIGURE A2: Southbay Dump Creek showing subhabitat features immediately after log placement. Date mapped August 28,29,1982. Stream discharge = 0.05 $m^3/s$**

SCALE

0 5 10 15 metres

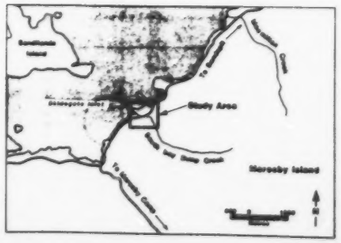
LEGEND

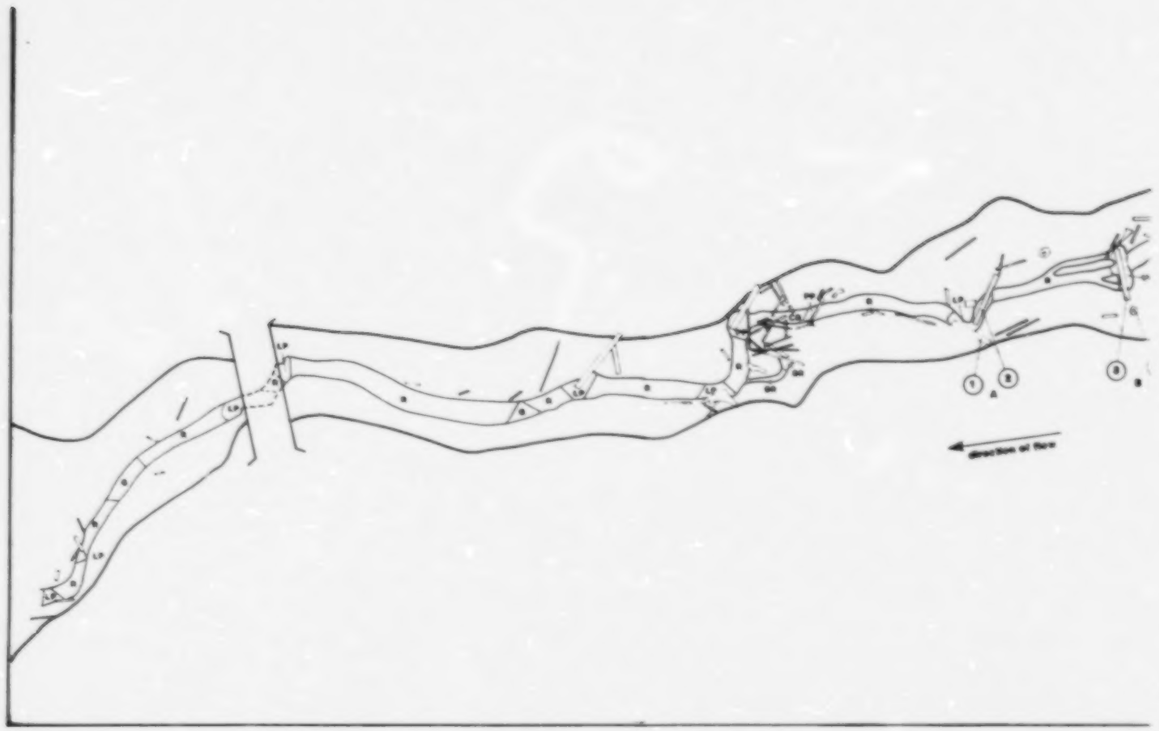
STREAM HABITATS

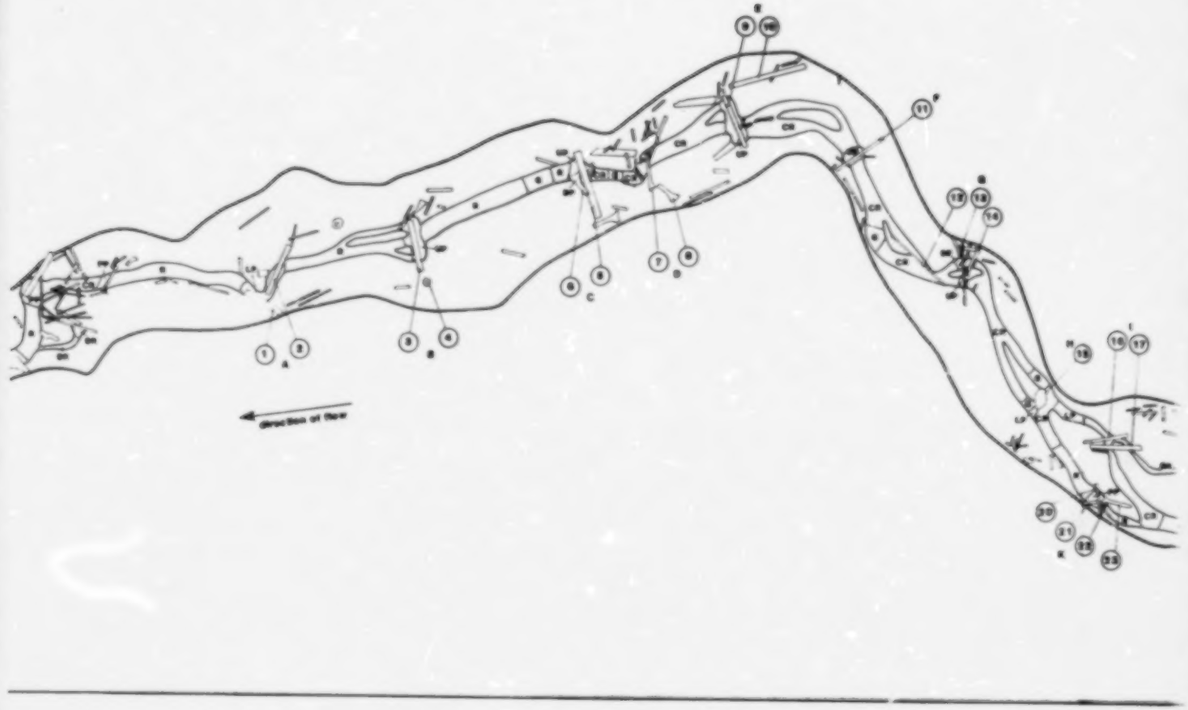
| | | | |
|---|---|---|---|
| LP | lateral scour pool | SP | side channel pool |
| PP | plunge pool | G | glide |
| DP | dammed pool | R | riffle |
| BP | backwater pool | CR | cascade riffle |
| UP | undercour pool | | |

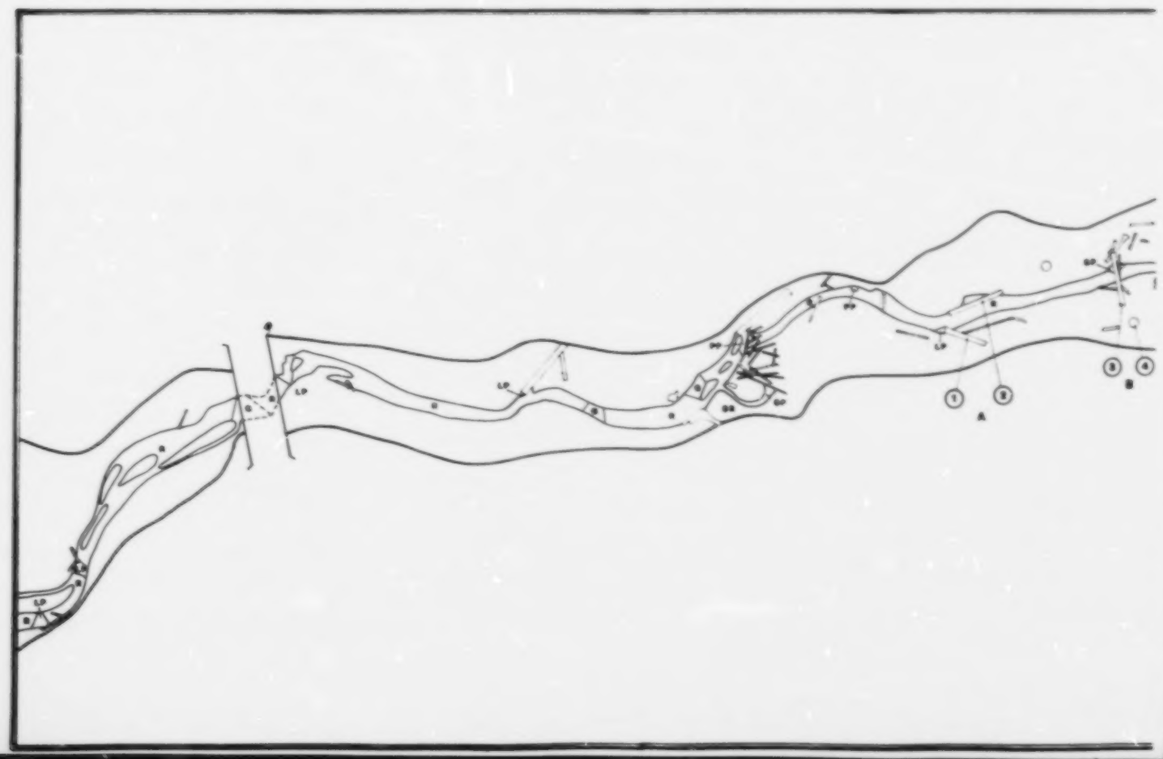
① debris pieces moved to test sites (August 16-18, 1982)

Ⓐ location of test site









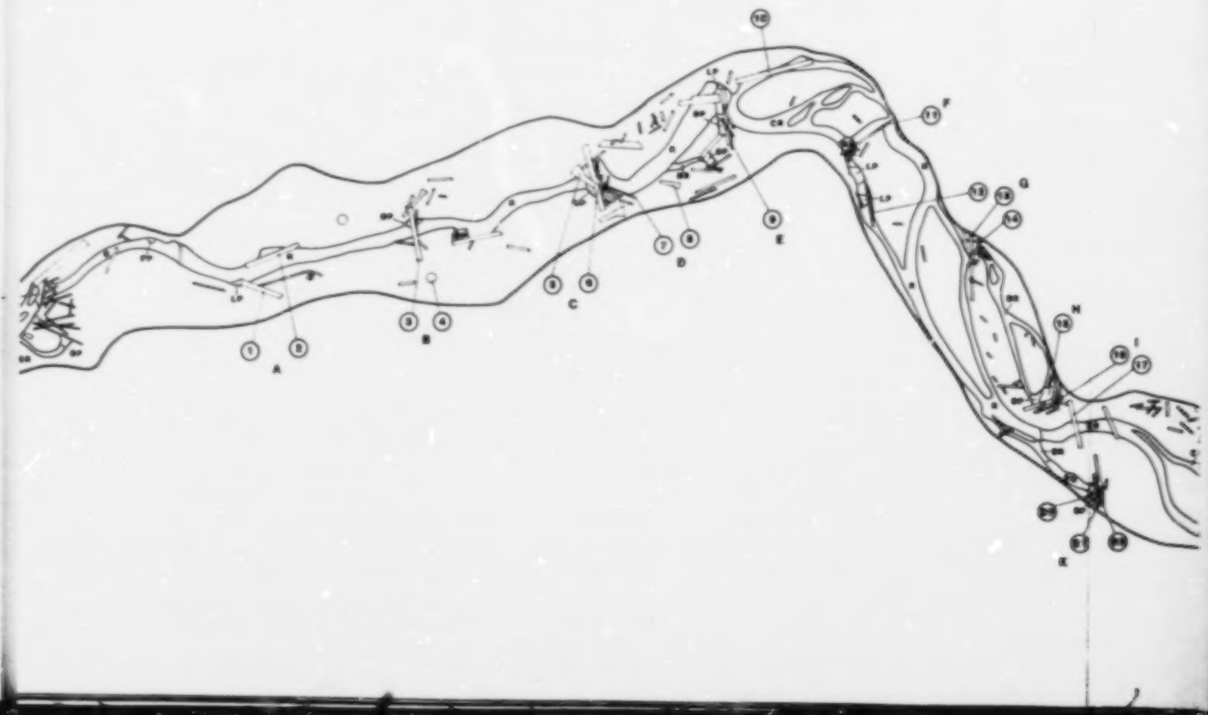


**FIGURE A3:** Southbay Dump Creek showing subhabitat features ten months after log placement.
Date mapped June 3, 1983.
Stream discharge = 0.09 $m^3/s$

SCALE

0 5 10 15 metres

LEGEND

STREAM HABITATS

| | | | |
|---|---|---|---|
| LP | lateral scour pool | SP | side channel pool |
| PP | plunge pool | G | glide |
| DP | dammed pool | R | riffle |
| BP | backwater pool | CR | cascade riffle |
| UP | undercocer pool | | |

① debris pieces moved to test sites. (August 10–12, 1982)

Ⓐ location of test sites

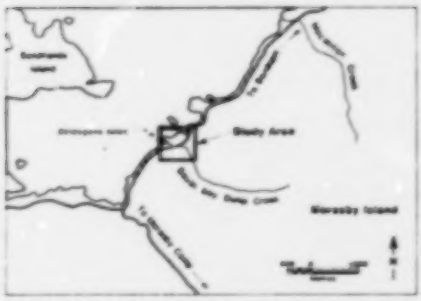


**FIGURE A4:** Southbay Dump Creek showing subhabitat features twelve months after log placement.
Date mapped August 24 & 25, 1983.
Stream discharge = 0.06 $m^3/s$

SCALE

0 5 10 15 metres

LEGEND

STREAM HABITATS

| | | | |
|---|---|---|---|
| LP | lateral scour pool | SP | side channel pool |
| PP | plunge pool | G | glide |
| DP | dammed pool | R | riffle |
| BP | backwater pool | CR | cascade riffle |
| UP | undercocer pool | | |

① debris pieces moved to test sites (August 10–12, 1982)

Ⓐ location of test sites